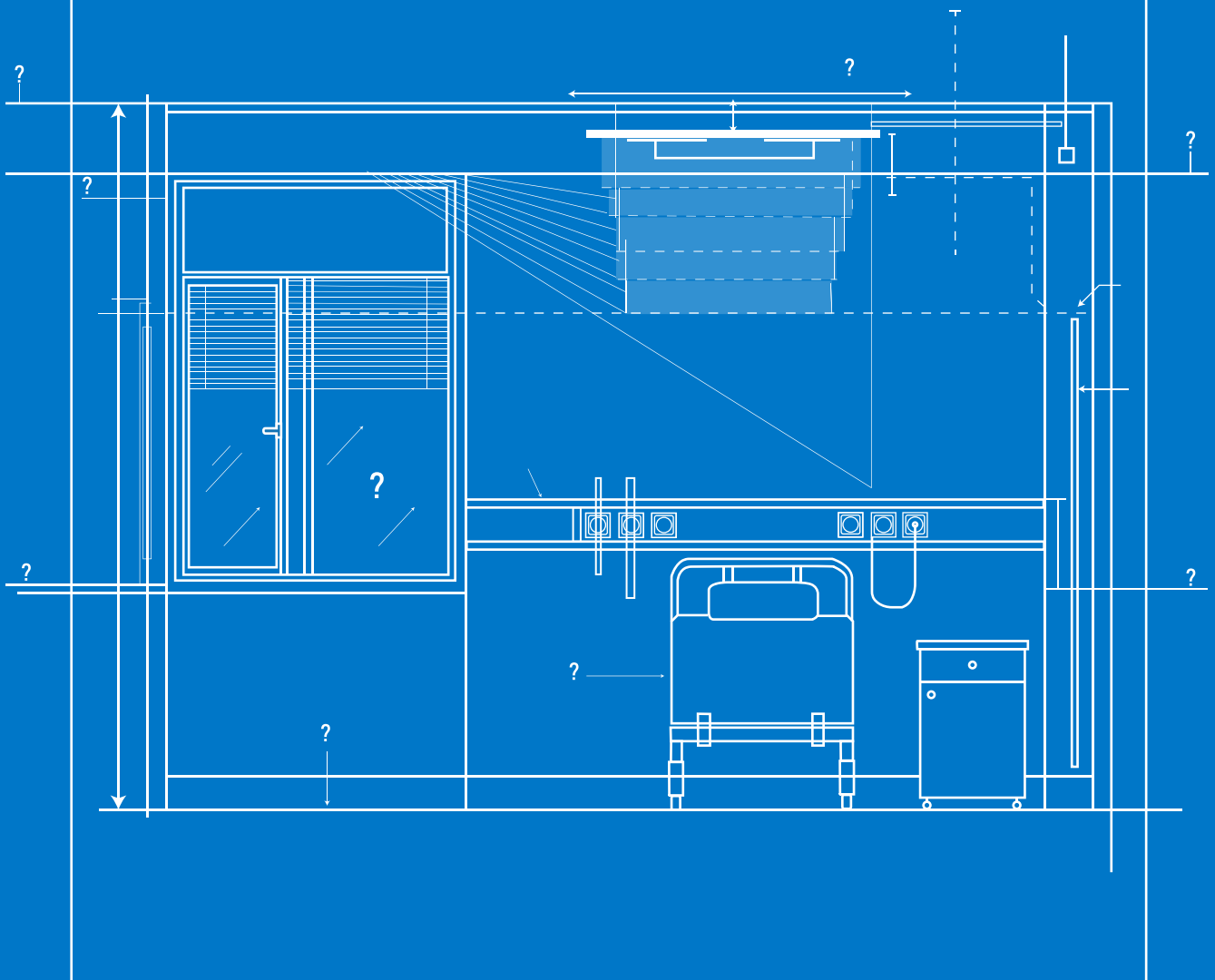


Towards Passive-First Healthcare Buildings

Occupant-centred evaluation of passive and hybrid cooling performance in Dutch hospital patient rooms under projected 2050 climate conditions



AR4B030 BT Graduation studio | June 2026

L.G.A. Buijssen (5321840)

Supervisors:
Prof.dr.ir. A.C. Boerstra
Dr. A. Luna Navarro

Delegate:
Tong Wang

External party:
Peter Buurman (Deerns)
Jeffrey van der Laag (Deerns)



PREFACE

This research is conducted within the Climate Design graduation track of the Building Technology master's programme at Delft University of Technology and developed in collaboration with the Building Physics and Energy team at Deerns. It focuses on thermodynamic heat exchange and thermal comfort evaluation, with particular attention to air and mean radiant temperature, air velocity, clothing insulation and metabolic rate.

ACKNOWLEDGEMENTS

I would first like to thank my university supervisors, Alessandra and Atze, for their guidance throughout this thesis. **Atze**, I have greatly appreciated your positive attitude, critical questions and the confidence you gave me during the process. **Alessandra**, thank you for your guidance, for safeguarding the academic quality of the work, and for the time and attention you invested in my research.

I would also like to thank my supervisors and **colleagues at Deerns**. I am grateful to the entire building physics team for the inspiring discussions and for allowing me to engage with the topic in a practical and professional environment. In particular, I would like to thank **Peter** for his substantive guidance, enthusiasm and critical reflection. I have very much enjoyed our discussions and always felt comfortable asking questions and testing ideas. I would also like to thank **Jeffrey** for making it possible for me to become part of the building physics team, for making me feel welcome at Deerns, and for helping me establish the necessary contacts.

Furthermore, I would like to thank the **real estate department of Erasmus MC** for enabling the case study and for the openness with which they contributed to this research. I am also grateful to **all interview participants** for their time, cooperation and willingness to reflect on the topic. These conversations were valuable not only for the technical and professional insights they provided, but also on a personal level. Speaking with people from different roles within healthcare design has been highly inspiring, and I will carry these perspectives with me in my future career.

Finally, I would like to thank my **friends, family, fellow students and Felix** for their support, patience and interest throughout the thesis process.

With pride, I present the final work of my graduation thesis.

ABSTRACT

Dutch hospital buildings face increasing cooling demand under projected 2050 climate conditions, while patient rooms must provide stable thermal comfort for users with different levels of vulnerability, activity and adaptive capacity. This thesis investigates how passive and hybrid cooling strategies at patient-room scale can support occupant-centred thermal comfort, reduce cooling demand and contribute to climate-resilient healthcare design.

The research combines a literature review, EnergyPlus-based simulations and stakeholder interviews. The literature review establishes the building-physics and thermal-comfort basis for passive and hybrid cooling. Afterwards, a representative Dutch hospital patient room is simulated under morphed 2050 climate conditions, using operative temperature, SET, PMV/PPD, cooling load and active cooling hours for staff, mobile patients and bedridden patients. Finally, stakeholder interviews examine how passive and hybrid cooling strategies are currently understood, constrained and implemented in healthcare design practice.

The results show that passive envelope measures reduce transmitted solar radiation up to 80%, but remain insufficient when internal heat gains, continuous occupancy and thermal storage dominate the room heat balance. Natural ventilation provides intermittent comfort benefits, whereas hybrid cooling with local air movement enables a higher mechanical cooling setpoint and reduces ideal cooling load under the tested assumptions.

The interviews show that implementation is constrained by fragmented requirements, risk-averse decision-making, infection-prevention concerns, cost allocation and an installation-led design culture. This thesis therefore concludes that passive cooling should not replace mechanical cooling in hospitals, but should form part of a passive-first hybrid design philosophy: reducing heat gains, managing internal loads, supporting heat dissipation and using active systems as controlled fallback rather than the default starting point.

Keywords - passive cooling; hybrid cooling; healthcare buildings; patient rooms; occupant-centred thermal comfort; natural ventilation; local air movement; cooling demand; future climate; building performance simulation

1. Introduction	8
1.1 Motivation and relevance	9
1.2 Research scope and typological focus	12
1.3 Problem statement	13
1.4 Objectives	13
1.5 Research questions	13
1.6 Research methodology	14
2. Literature review	16
2.1 Passive cooling potential and design uncertainty in healthcare buildings	17
2.2 Building heat balance and passive cooling mechanisms	18
2.3 Physiological heat balance of human body and thermal comfort	26
2.4 Sub-conclusion literature review	33
3. Case study description	34
3.1 Case study description – Erasmus MC SPOT	35
3.2 User profiles	36
3.3 Programme of requirements	37
4. Energy and thermal comfort performance (simulation)	38
4.1 Simulation objective and methodology	39
4.2 Simulation results	44
4.3 Simulation discussion and limitations	58
4.4 Sub-conclusion energy and thermal comfort performance	61
5. Implementation barriers and drivers (interviews)	62
5.1 Stakeholder interview objective and methodology	63
5.2 Qualitative interview results	64
5.3 Quantitative interview results	72
5.4 Design and process recommendations	75
5.5 Interview discussion and limitations	83
5.6 Sub-conclusion implementation barriers and drivers	83
6. Discussion, conclusion and reflection	84
6.1 Cross-chapter discussion	85
6.2 Final conclusion	89
6.3 Reflection	91
7. References	94
8. Appendices	98

1. Introduction	8
Figures	
1.1: Positioning of research focus.	9
1.2: Trias Energetica principle.	9
1.3: Nightingale Ward hospitals, Florence Nightingale, ca. 1860s.	11
1.4: Zonnestraal Sanatorium, Jan Duiker, 1928.	11
1.5: Paimio Sanatorium, Alvar Aalto. 1933.	11
1.6: Butaro District Hospital, MASS Design Group, 2011.	11
1.7: Schematic overview of research methodology.	15
2 Literature review	16
Figures	
2.1: MacLeamy's curve.	17
2.2: Conventional design process for healthcare buildings.	17
2.3: Simplified heat balance in a schematic section.	18
2.4: Abstract principles of heat-gain prevention, modification and dissipation.	18
2.5: Abstract window cross-section showing heat-gain prevention mechanisms.	19
2.6: Simplified schematic overview of heat-gain modification in a building section.	20
2.7: Simplified schematic overview of convective heat dissipation.	21
2.8: Typical logarithmic power spectrum curves of (a) natural wind and (b) mechanical airflow.	22
2.9: Simplified schematic overview of latent heat dissipation.	23
2.10: Simplified schematic overview of ground-coupled heat dissipation.	23
2.11: Human heat balance & Fanger parameters.	27
2.12: a. Comfort diagrams for seated patients in summer (0.6clo, airspeed ≤ 0.15 m/s).	29
b. Comfort diagrams for lying patients in summer (1.9clo, airspeed ≤ 0.15 m/s).	
Tables	
2.1: Categorisation and explanation of individual passive cooling strategies	25
2.2: Influence of elevated air speed on acceptable operative temperature ranges in selected thermal comfort studies.	31
3. Case study description	34
Figures	
3.1: 2D plan view of the current Erasmus MC situation.	35
3.2: 3D volume study of the Erasmus MC expansion, with the case-study wing marked in blue.	35
3.3: Case-study floor plan of building level 6, with the representative patient room highlighted in blue.	35
3.4: Summary of user profile.	36
Tables	
3.1: Programme of Requirements for the case study simulation.	37
4. Energy and thermal comfort performance (simulation)	38
Figures	
4.1: Simulation workflow energy and thermal comfort performance.	39
4.2: Simulation model overview: (a) isometric view of the southwest Honeybee model with adiabatic boundary surfaces, except for the southwest façade; (b) wireframe plan with sensor points at the window location, bed position and staff zone; (c) simulation context.	40
4.3: Abstract simulation scenarios: (a) freefloating, (b) HVAC baseline and (c) passive envelope.	42
4.4: Abstract simulation scenarios: (a) Natural ventilation, (b) Local fans, (c) Hybrid operation.	43
4.5: Hourly dry-bulb temperature from 1 June to 31 August for 2025 and 2050 weather scenarios.	44
4.6: Hourly SET from 1 June to 31 August for the HVAC baseline scenario using the 2025 EPW weather file, shown for mobile patients, bedridden patients and staff.	45
4.7: Hourly SET from 1 June to 31 August for the HVAC baseline scenario using the 2050 EPW weather file, shown for mobile patients, bedridden patients and staff.	45
4.8: Hourly SET and (T_o) for the HVAC baseline mobile-patient profile on 1 August (left) and 3 June (right), shown for the 2025 and 2050 weather scenarios.	45
4.9: Graph showing SET over summer period for the freefloating and passive envelope scenario using EPW data file 2050, showing mobile patients.	46
4.10: Hourly T_o over the summer period for the passive-envelope scenario with reduced internal heat gains.	47
4.11: Outdoor v_{air} at measuring location in De Bilt over the summer period.	48
4.12: Hourly $v_{air,window}$ over the summer period.	48
4.13: Hourly wind speed for three critical days within the summer period.	49
4.14: Hourly SET for mobile patients over the summer period, including sensible heat removal through ventilation.	49

4.15: Hourly SET for mobile patients over the summer period, including sensible and latent heat removal through ventilation.	49
4.16: Delta SET over the summer period for scenario natural ventilation.	50
4.17: Dot plot of hourly SET and T_o for mobile patient during the summer period.	51
4.18: Dot plot of hourly SET and T_o for bedridden patient during the summer period.	51
4.19: Dot plot of hourly SET and T_o for staff during the summer period.	51
4.20: Local fan activation for mobile patients based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.	53
4.21: Local fan activation for bedridden patients based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.	53
4.22: Local fan activation for staff based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.	53
4.23: Hourly SET plot over the summer period for the hybrid scenario mobile patient.	55
4.24: Hourly SET plot over the summer period for the hybrid scenario bedridden patient.	55
4.25: Hourly SET plot over the summer period for the hybrid scenario staff.	55
4.26: Hourly active-cooling status for the HVAC baseline scenario.	56
4.27: Hourly active-cooling status for the hybrid operation scenario.	56
4.28: Hourly plot with the cooling load for the HVAC baseline scenario.	57
4.29: Hourly plot with the cooling load for the hybrid operation scenario.	57

Tables

4.1: Fixed inputs for the performance simulation of the case study.	40
4.2: First-order cost reduction estimation HVAC baseline scenario versus hybrid scenario.	58

5. Implementation barriers and drivers (interviews)

Figures

5.1: Interview cards for relative ranking and think-out-loud exercise.	62
5.2: Summary diagram of implementation barriers from the qualitative interview results.	63
5.3: Box plot showing the relative ranking of implementation barriers.	71
5.4: Box plot showing the relative ranking of implementation drivers.	72
5.5: Spearman rank correlation between participating stakeholders.	73
5.6: Cards from the passive-first dialogue starter card set	74
5.7: Focus group workshop on passive natural ventilation in patient rooms.	75
5.8: Summary of design objectives.	78
5.9: Design exploration: Ceiling-integrated air distribution.	79
5.10: Design exploration: Bed-integrated microclimate and separate airflow zones.	80
5.11: Design exploration: Aerodynamic solar shading and Coandă-based airflow guidance.	80
5.12: Pressure-buffer façade with distributed air intake.	81
5.13: Design exploration of passive-first and hybrid cooling strategies at patient-room scale.	81
	82

Tables

5.1: Translating barriers and drivers into 6 P conditions.	75
--	----

6. Discussion, conclusion and reflection

7. References

8. Appendices

ABBREVIATIONS

ACH - Air Changes per Hour	TI - Turbulence intensity
ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers	P_a - Water vapour pressure
Bbl - Besluit Bouwwerken Leefomgeving	PAL - Physical Activity Level
BENG - Bijna-Energieneutrale Gebouwen	PCM - Phase Change Material
CBS - Centraal Bureau voor de Statistiek	PMV - Predicted Mean Vote
Cfb - Köppen climate classification	PPD - Predicted percentage dissatisfied
CFD - Computational Fluid Dynamics	PvE - Programme of Requirements
CIBSE - Chartered Institution of Building Services Engineers	REE - Resting energy expenditure
CLO - Clothing insulation	RH - Relative Humidity
COP - Coefficient of Performance	RQ - Research Question
DR - Draught rate	RIVM - Rijksinstituut voor Volksgezondheid en Milieu
EPW - EnergyPlus weather file	R_t - Total thermal resistance
HVAC - Heating, Ventilation and Air Conditioning	RVO - Rijksdienst voor Ondernemend Nederland
IAQ - Indoor Air Quality	SET - Standard effective temperature
IEA - International Energy Agency	SHARP - Solar Horizontal Angle Relative to Person
IEQ - Indoor Environmental Quality	TCO - Total cost of ownership
ISO - International Organization for Standardization	T_a - Air temperature
KNMI - Koninklijk Nederlands Meteorologisch Instituut	T_o - Operative temperature
KPI - Key Performance Indicator	T_r - Mean radiant temperature
MET - Metabolic rate	TMY - Typical Meteorological Year
MPG - Milieuprestatie Gebouwen	T_{sk} - Skin temperature
MRT - Mean Radiant Temperature	TSV - Thermal sensation vote
NEN - Nederlandse Norm	UHI - Urban Heat Island
NTA - Nederlandse Technische Afspraak	U-value - Thermal transmittance (W/m ² K)
	v_{air} - Air speed/velocity
	VLT - Visible Light Transmittance
	WWR - Window-to-Wall Ratio

1

INTRODUCTION

This chapter introduces the motivation, relevance and context of the research by positioning passive cooling in healthcare environments within the broader challenge of future climate resilience. It defines the research problem, scope, objectives and research questions, and outlines the methodological approach that structures the subsequent chapters.

1.1 Motivation and relevance

Buildings accommodate care, work, learning and living, activities that increasingly take place indoors. In the Netherlands, people spend between 80% and 90% of their time inside buildings (Betgen et al., 2024, p. 30). As a result, the quality of the indoor environment has become strongly dependent on the way buildings are designed, operated and conditioned. This is particularly relevant for thermal comfort, as buildings must increasingly limit overheating while maintaining healthy and comfortable indoor conditions.

Architectural practice continues to rely predominantly on mechanical climate control, with active systems often oversized to compensate for design uncertainty and operational risk (Attia et al., 2012; Attia, 2018; Anand et al., 2023). These systems are energy- and material-intensive, contribute substantially to greenhouse gas emissions and resource use, and require extensive technical components and maintenance (IEA et al., 2022). This dependency may reduce robustness, shortening service life and raising life-cycle costs (Arowoia et al., 2024).

In the Netherlands, the built environment accounts for approximately 35% of national energy use and 25% of total CO₂ emissions (Centraal Bureau voor de Statistiek, 2025a), with climate control systems responsible for nearly half of building-related energy demand (Zarco-Soto et al., 2025). Cooling demand is expected to increase as climate change raises overheating risks in temperate climates (KNMI, 2023; Prieto et al., 2018; Laouadi et al., 2023). The growing adoption of air conditioning reflects this trend, reinforcing energy demand and contributing to outdoor heat accumulation.

A promising direction lies in the use of passive design strategies for cooling: design measures that enhance indoor environmental quality (IEQ) by harnessing natural energy flows rather than relying primarily on mechanical or electrical systems (Konstantinou & Prieto Hoces, 2018). Passive cooling can therefore be understood as a building-physics-based approach in which heat gains, heat storage, heat dissipation, airflow and solar exposure are controlled through architectural, spatial and material decisions. These strategies could reduce intrinsic cooling demand, but their implementation remains limited by uncertainty regarding reliability, performance potential and user-specific comfort effects. Their effectiveness depends on the interaction between climate, building geometry, façade configuration, ventilation principles, material choices and behavioral patterns. Therefore, passive cooling cannot be approached as a set of isolated measures, but should be understood as an integrated design approach.

Focusing on reducing cooling demand from a building-physics perspective is consistent with the Trias Energetica framework, originally formulated in 1996 by Lysen and later adopted by RVO in the Netherlands (Infoblad Trias Energetica en Energieneutraal Bouwen, 2013). The framework identifies that the first and most effective sustainability strategy is to reduce the intrinsic energy demand of a building before adding mechanical systems.

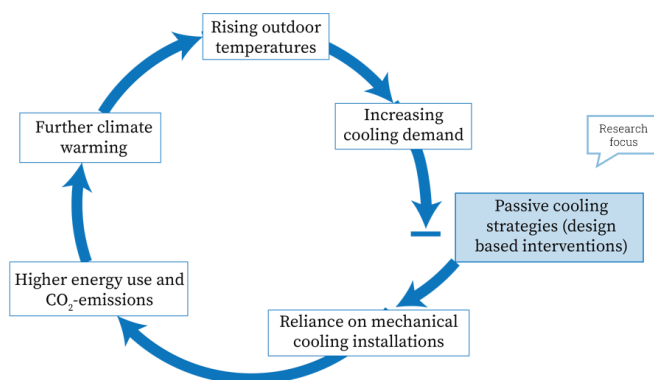


Fig. 1.1: Positioning of research focus (Author's work)

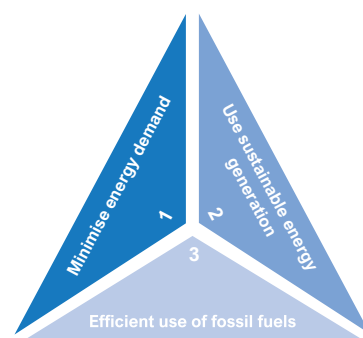


Fig. 1.2: Trias Energetica principle. Redrawn and adapted from Lysen (1996).

The effect of passive cooling is highly context-dependent, shaped by climate, design decisions and operation (Maghami et al., 2025). The Netherlands provides a relevant context because its building stock faces a shifting balance between heat retention in winter and heat mitigation in summer. Climate change is expected to reduce night-time cooling potential, increase humidity levels and alter solar gain patterns (Heiranipour et al., 2025; KNMI, 2023), implying that strategies effective under current conditions may no longer perform sufficiently in the future.

Current overheating-risk mitigation often relies on technological redundancy and backup cooling capacity, rather than on reducing the building's intrinsic sensitivity to heat. Passive cooling is therefore both promising and uncertain: it can lower cooling demand and reduce dependence on mechanical systems, but its future performance must be explicitly assessed rather than assumed.

This is particularly relevant in early design stages, where decisions on orientation, façade configuration, ventilation principles and material choices strongly influence later cooling demand, overheating risk and system dependency. However, passive measures are often assessed qualitatively, while reliable quantitative feedback is lacking when design freedom is still high (MacLeamy, 2004; Hopfe & Hensen, 2011). As simulation expertise is frequently introduced only after key design choices have been fixed, opportunities to integrate passive cooling as a fundamental design strategy are reduced (Bhatia et al., 2024).

Relevance for healthcare buildings

Within the Dutch building context, healthcare represents a particularly critical sector, accounting for approximately 7% of national greenhouse gas emissions (Rijksoverheid, 2022; Steenmeijer et al., 2022). Healthcare facilities must reduce energy use while maintaining strict requirements for thermal comfort, air quality and hygiene, particularly for vulnerable occupants. This often results in sealed façades and a strong dependence on mechanical climate control. In such environments, thermal discomfort or system failure affects not only user satisfaction but also patient health, recovery and operational continuity (Lomas & Porritt, 2016; Boerstra et al., 2021).

Demographic change further increases the relevance of this challenge. In the Netherlands, the population aged 80 and over is projected to grow from approximately 0.9 million in 2025 to more than 2.1 million in 2070 (Centraal Bureau voor de Statistiek, 2025b), increasing demand for healthcare facilities. Reducing cooling demand in this sector is therefore both an environmental and operational priority.

Despite extensive research on thermal comfort in offices and residential buildings, quantitative evidence on thermal comfort in healthcare environments remains limited, particularly for different user groups such as staff, mobile patients and immobile patients. Existing comfort models are largely based on healthy, seated adults and may not adequately represent the thermophysiological constraints of vulnerable users. Moreover, the interaction between passive ventilation, elevated air speed and occupant-specific heat balance in spatially non-uniform environments remains insufficiently understood.

Historical development of passive cooling in healthcare architecture

Passive cooling predates mechanical HVAC systems and is rooted in climatic responsiveness and material logic. Historically, healthcare architecture relied on such strategies to provide hygienic and thermally acceptable environments.

A well-known example is the pavilion hospital typology promoted by Florence Nightingale (Fig. 1.3), where elongated wards, opposing operable windows and high ceilings supported cross-ventilation, contaminant dilution and patient recovery.

Similarly, the Zonnestraal Sanatorium applied orientation, lightweight construction and fully operable façades to maximise solar exposure and fresh air supply, aiming to improve recovery outcomes for tuberculosis patients through controlled environmental conditions (Fig. 1.4).

In the Paimio Sanatorium, designed by Alvar Aalto, passive cooling was embedded through building orientation, external shading and carefully directed airflow around patients, with the goal of creating an indoor climate that reduced physiological stress (Fig. 1.5).

More recently, the Butaro District Hospital by MASS Design Group demonstrates how natural ventilation, thermal mass and site positioning can be used to maintain acceptable indoor temperatures while reducing airborne infection risks (Fig. 1.6).

These examples illustrate that passive cooling was not only a necessity due to limited access to energy, but also a design strategy embedded in healthcare architecture, aimed at improving health outcomes.

With the widespread adoption of mechanical systems in the mid-twentieth century, passive principles were increasingly deprioritised, resulting in buildings with reduced climatic resilience and greater dependence on energy-intensive cooling. However, contemporary healthcare buildings face different constraints, including higher spatial density, outdoor pollution and noise, stricter infection-control requirements and increased demand for thermal stability. Historical passive principles therefore cannot be directly reintroduced, but must be reinterpreted.

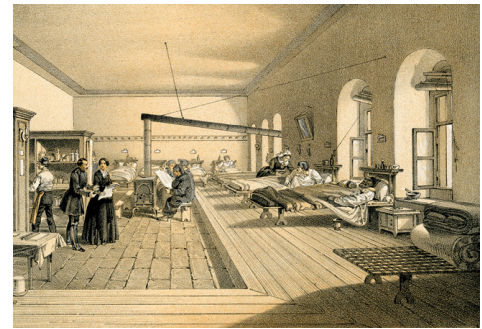


Fig. 1.3: Nightingale Ward hospitals, Florence Nightingale, ca. 1860s (Day&Son)



Fig. 1.4: Zonnestraal Sanatorium, Jan Duiker, 1928 (Vbnb, 2025)



Fig. 1.5: Paimio Sanatorium, Alvar Aalto, 1933 (Alvar Aalto Foundation, 2025)



Fig. 1.6: Butaro District Hospital, MASS Design Group, 2011 (Butaro District Hospital, 2011.)

1.2 Research scope and typological focus

This research focuses on new hospital buildings, with particular attention to standard low-risk patient rooms in inpatient care environments. This scope aligns with the selected case study and the Dutch Besluit bouwwerken leefomgeving (Bbl) category gezondheidszorgfunctie met bedgebed, which refers to healthcare functions where patients stay overnight and continuous care, supervision and indoor environmental control are required.

Patient rooms form a critical case for passive cooling because they combine 24/7 operation, high internal heat loads, strict comfort and hygiene requirements, and vulnerable occupants. These conditions allow limited tolerance for performance failure and make patient rooms suitable for examining thermal robustness, system dependency and design trade-offs over long operational lifetimes.

The research is limited to new construction, where passive cooling strategies can still be integrated spatially, technically and energetically from the outset. This makes the schematic design phase particularly relevant, as early decisions on orientation, façade design, room layout and system principles strongly influence later comfort performance, cooling demand and the economic value of passive measures.

High-risk healthcare spaces, such as operating rooms, intensive care units and isolation rooms, fall outside the scope of this study. These spaces are characterised by critical infection-control requirements, unstable or highly vulnerable patients, procedure-specific indoor climate conditions, specialised air treatment and pressure regimes. Existing building renovation and detailed HVAC system design are also excluded.

Although the simulations and interviews are situated within the hospital context, the findings are reflected upon in relation to other forms of healthcare real estate, such as nursing homes and long-term care facilities. Transferability is not assumed directly, but considered in relation to typological differences in internal loads, user vulnerability, adaptive capacity and operational constraints.

1.3 Problem statement

Despite growing research on passive cooling and thermal comfort, limited quantitative insight exists into passive cooling performance in hospital buildings, particularly at patient-room scale. Passive strategies are often assessed in isolation and evaluated mainly through energy demand or indoor air temperature, while occupant-centred thermal comfort remains insufficiently integrated (Maghami et al., 2025; Balali & Valipour, 2020).

The academic knowledge gap lies in understanding which passive cooling measures are suitable for patient rooms, how early-stage design parameters influence cooling demand and occupant-specific thermal comfort, and how such measures can be integrated into hospital design processes under realistic technical and organisational constraints.

1.4 Objectives

This research aims to assess the potential of passive and hybrid cooling strategies at patient-room scale to support user-specific thermal comfort, reduce overheating risk and limit active cooling demand in hospital buildings. Combining simulation-based assessment with stakeholder insights, it develops design guidance for occupant-centred cooling in early-stage hospital design.

The academic contribution is an occupant-centred assessment logic that reframes passive-first cooling as a sequence of room-level load reduction, user-specific comfort evaluation and hybrid mechanical fallback.

- **Building-physics mechanisms:** identify the mechanisms linking passive design to heat exchange, indoor conditions and overheating risk.
- **User-specific comfort limits:** define comfort boundaries for mobile patients, bedridden patients and staff.
- **Passive envelope performance:** assess the effect of solar control, glazing and internal heat gains under projected 2050 climate conditions.
- **Occupant-level air movement:** evaluate natural ventilation and local fans as occupant-cooling mechanisms.
- **Design integration and implementation:** translate technical and stakeholder findings into early-stage design guidance.

1.5 Research questions

RQ: How can passive and hybrid cooling strategies at patient-room scale support occupant-centred thermal comfort and reduce cooling demand in Dutch hospital buildings under projected 2050 climate conditions?

- RQ1:** Which building-physics mechanisms determine how passive design strategies affect occupant-level heat exchange, indoor thermal conditions and overheating risk in patient rooms?
- RQ2:** How do thermal comfort limits differ between healthcare user profiles, such as mobile patients, bedridden patients and staff in relation to metabolic rate, clothing insulation, exposure duration and adaptive capacity?
- RQ3:** To what extent can passive envelope measures reduce overheating risk and cooling demand in patient rooms under projected 2050 climate conditions?
- RQ4:** How can occupant-level air movement through natural ventilation and local fans improve thermal comfort for different healthcare users and support higher mechanical cooling setpoints?
- RQ5:** How can simulation-based performance insights and stakeholder perspectives on implementation barriers, drivers and design-process conditions be translated into early-stage design guidance for robust, occupant-centred cooling strategies in healthcare buildings?

1.6 Research methodology

This section outlines the overall research methodology, combining literature review, user-profile definition, building performance simulation and stakeholder interviews. The specific simulation and interview methodologies are described in Sections 4.1 and 5.1, respectively.

Literature review (RQ 1-2)

A structured literature review was conducted to establish the theoretical basis for occupant-centred passive cooling in healthcare buildings. The review synthesises knowledge on passive cooling mechanisms, thermal comfort theory and healthcare-specific indoor environmental requirements.

The review serves three main purposes. Firstly, it defines the building-physics principles underlying passive cooling, including heat gain prevention, heat modification and heat dissipation. Second, it examines how thermal comfort theory can be applied to healthcare users with different metabolic rates, clothing insulation, exposure durations and adaptive capacities. Third, it translates these principles into quantitative performance indicators, including PMV, SET and user-specific comfort limits, which inform the subsequent simulation assessment.

The literature search was conducted iteratively using Scopus, Web of Science, ScienceDirect, SpringerLink and the TU Delft Repository. Professional and regulatory sources, including KNMI, RVO, RIVM, ASHRAE, CIBSE and Dutch standards such as BBL, BENG, ISSO 74 and NTA, were consulted where design or regulatory context was required. Search terms were clustered around passive cooling mechanisms, air movement, healthcare typologies, Dutch climate conditions, regulatory frameworks and thermal comfort models (Appendix A). Sources were selected based on peer-review status or institutional authority, methodological transparency, publication date and relevance to passive cooling, healthcare environments and occupant-level comfort assessment.

Definition of user profiles and programme of requirements (RQ2)

To enable occupant-centred assessment, three healthcare user profiles are defined: staff, mobile patients and bedridden patients. For each profile, clothing insulation, metabolic rate, exposure duration and adaptive capacity are derived from literature and regulatory guidance. These parameters are translated into user-specific comfort boundaries using established indices, including PMV and SET, and form the performance criteria for the simulation analyses.

Simulation-based evaluation of passive and hybrid cooling performance (RQ 3-4)

A representative Erasmus MC case-study model is developed, focusing on standard patient rooms and 24-hour care zones. The model reflects typical spatial and façade characteristics of Dutch hospital buildings and serves as the reference configuration for the simulation study.

Dynamic thermal simulations are performed in EnergyPlus through Rhino/Grasshopper and Honeybee, allowing parametric control over geometry, façade configuration and ventilation-related variables. The detailed simulation methodology, including assumptions, input parameters, boundary conditions, software workflow and scenario definitions, is described in Section 4.1.

The simulation study evaluates free-floating, mechanically cooled, passive and hybrid scenarios under projected 2050 climate conditions using morphed EPW weather files. Performance is assessed through operative temperature, cooling demand, overheating risk, air velocity and user-specific comfort responses. The analysis specifically examines whether improved passive conditions and occupant-level air movement through natural ventilation or local fans can support higher mechanical cooling setpoints while maintaining comfort. This positions passive cooling not as a full replacement for mechanical systems, but as part of a hybrid passive-active cooling approach. The results identify when passive measures can reduce active cooling dependency, where mechanical fallback remains necessary and how these findings can inform later design guidance.

Design integration and implementation analysis (RQ5)

To connect the technical findings to design practice, stakeholder interviews are conducted with professionals involved in the design, assessment and operation of hospital and healthcare environments. The interviews include stakeholders from healthcare real estate, building services engineering, architecture, indoor environmental quality and related decision-making roles.

The interviews consist of two parts. The first part is semi-structured and explores current cooling practices, experiences with passive cooling, thermal comfort governance, design responsibilities and decision-making processes in healthcare projects. This part provides insight into how passive cooling is currently understood, at which stages of the design process it is considered, and which institutional or technical constraints influence its implementation.

The second part is structured and focuses on the evaluation of the implementation barriers and potential drivers. Participants complete a relative ranking exercise while thinking aloud to understand their reasoning. The qualitative and quantitative findings are combined to understand decision-making patterns in healthcare design practice.

The findings from the simulations and interviews are combined into design-oriented guidance for early-stage decision-making. This synthesis links user-specific comfort boundaries, spatial mechanisms for indoor air movement and thermal robustness outcomes with stakeholder-based insights into implementation barriers, drivers and process conditions. The final output is a design-support tool that helps stakeholders identify under which conditions passive cooling strategies can be responsibly integrated into healthcare buildings while reducing dependence on active cooling systems.

Use of artificial intelligence

Artificial intelligence was used as a supporting tool in this thesis, primarily to check spelling and grammar, refine Python code for the visualisation of simulation results, and discuss possible approaches for diagrams and figures. All figures in this thesis were ultimately designed and produced entirely by the author.

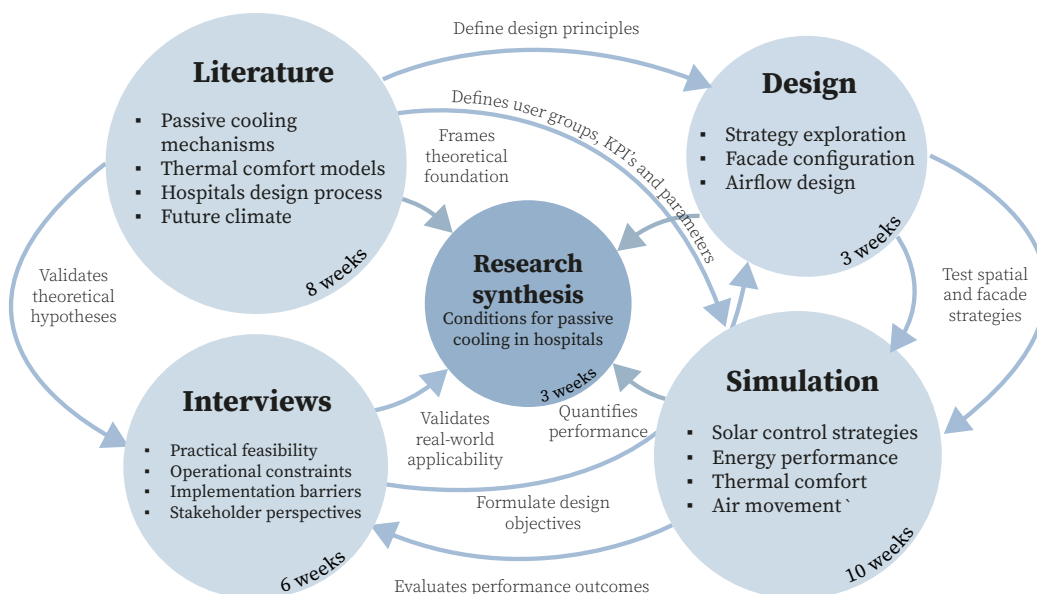


Fig. 1.7: Schematic overview of research methodology. (Author's work)

2

LITERATURE REVIEW

The literature review establishes the building-physics basis for passive and hybrid cooling in healthcare environments. It links heat gains, thermal storage, heat dissipation and air movement to occupant-level thermal comfort, and defines the comfort boundaries, design scope and evaluation criteria used in the subsequent simulation study.

2.1 Passive cooling potential and design uncertainty in healthcare buildings

Since 2020, recent literature has shown a strong increase in research on passive cooling strategies (Maghami et al., 2025). Simulation studies in temperate maritime climates comparable to the Dutch context indicate that relatively simple design measures can substantially reduce cooling demand. Building-form optimisation can improve energy performance by around 20% (Lu et al., 2019), while combinations of glazing optimisation, solar shading and natural ventilation can maintain acceptable summer comfort for up to 90% of occupied hours in Dutch high-rise buildings (Raji et al., 2017). Similar reductions in cooling demand are reported for cross-ventilation, night flushing and thermal mass integration (Raji et al., 2019). International studies report comparable magnitudes, with natural ventilation reducing cooling energy use by up to 40% and fixed shading by approximately 25% (Zhang et al., 2019).

Despite this potential, reported performance varies widely. Passive cooling effectiveness is highly context dependent, as strategies influence multiple components of the building heat balance and are typically evaluated relative to project-specific reference scenarios. Their performance depends strongly on climatic conditions, solar exposure, building geometry and diurnal temperature variation, which complicates comparison between studies (Prieto Hoces et al., 2018).

Although uncertainty in building design has been widely studied, limited insight exists into how early-stage uncertainties propagate through passive cooling strategies and affect energy use, thermal comfort and long-term performance, particularly in low-energy and healthcare buildings (Kotireddy et al., 2019). Existing research typically addresses uncertainties in isolation, focusing on phenomena such as night ventilation performance, daylight variability, radiative cooling or wind-driven ventilation sensitivity, while their combined effects remain insufficiently quantified. Similarly, few studies provide actionable guidance for managing anticipated and unanticipated uncertainties in early design (Kotireddy et al., 2019). Early-stage design-support approaches can provide rapid performance feedback and support energy-efficient decision-making. However, they rarely address passive cooling strategies or the specific constraints of healthcare environments (Attia et al., 2018). Appendix B provides a preliminary overview of the design uncertainties involved in passive design strategies.

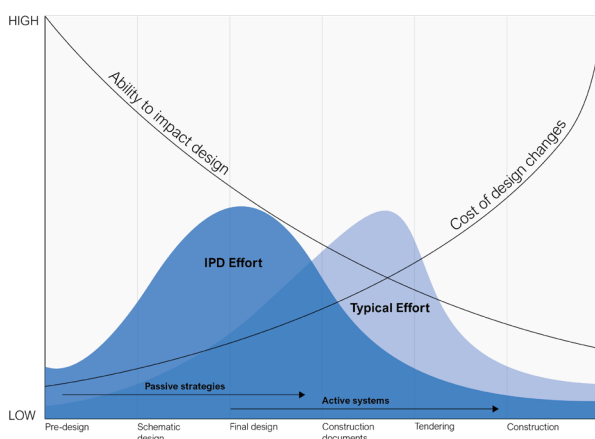


Fig. 2.1: MacLeamy's curve, redrawn and adapted from MacLeamy (2004).

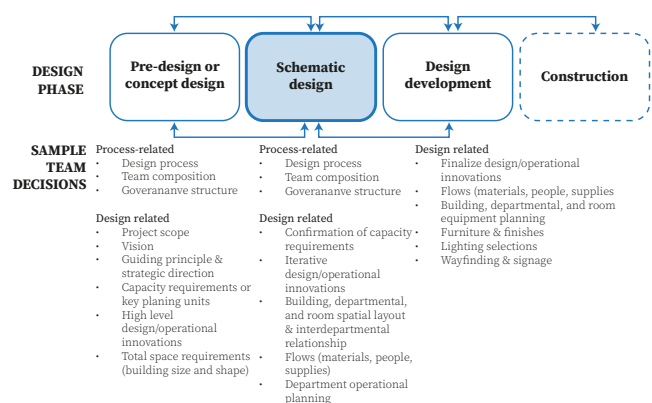


Fig. 2.2: Conventional design process for healthcare buildings, redrawn and adapted from Gittler and Lam (2025).

2.2 Building heat balance and passive cooling mechanisms

Passive cooling mechanisms influence indoor environmental conditions by acting directly on the fundamental heat-transfer processes that govern the building heat balance (Konstantinou & Prieto Hoces, 2018). External climatic drivers such as solar radiation, outdoor air temperature ($T_{a,out}$) and wind act on the building envelope, which determines solar gains (Q_{solar}), transmission losses (Q_{trans}) and ventilation potential (Q_{vent}). These heat gains (Q_{gains}) and losses (Q_{losses}) are subsequently buffered, delayed or redistributed through thermal mass and spatial configuration, resulting in indoor conditions. Only when these processes are insufficient to maintain comfort within defined limits, additional cooling is needed. Cooling demand is a consequence of the heat balance, and passive strategies intervene in this balance. Fig. 2.3 schematically illustrates these interactions, emphasising that passive cooling strategies intervene at multiple stages of the heat balance rather than at a single point. From a building-physics perspective, this relation can be expressed through a simplified heat balance in line with ISO 52016-1:

$$\sum Q_{gains} - \sum Q_{losses} - \frac{dQ_{storage}}{dt} = Q_{cooling} \quad \text{Eq. 1}$$

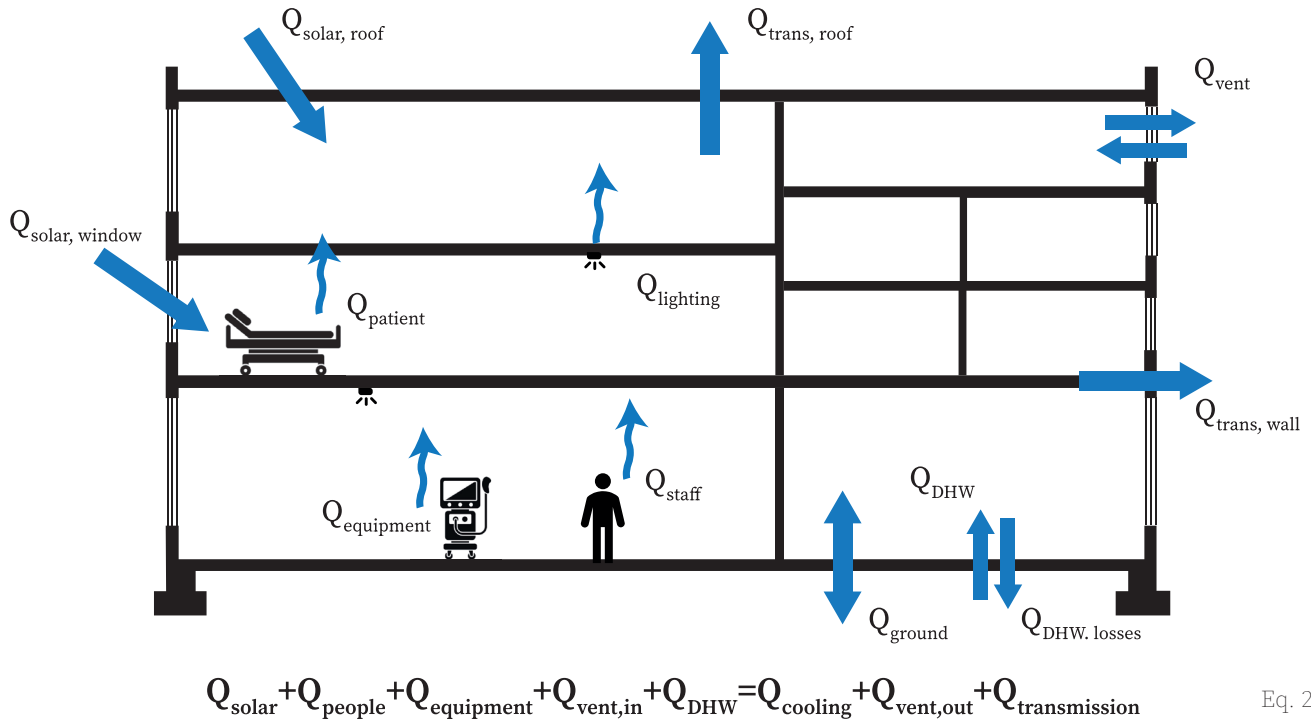


Fig. 2.3: Simplified heat balance in a schematic section. (Author's work)

Passive cooling mechanisms can be classified according to the dominant physical process by which they act on the described heat balance. Following the internationally recognised classification of Santamouris (2012), also adopted in recent frameworks such as IEA Annex 80 (2021), a distinction is made between heat-gain prevention, heat-gain modification and heat-gain dissipation (Fig. 2.4).

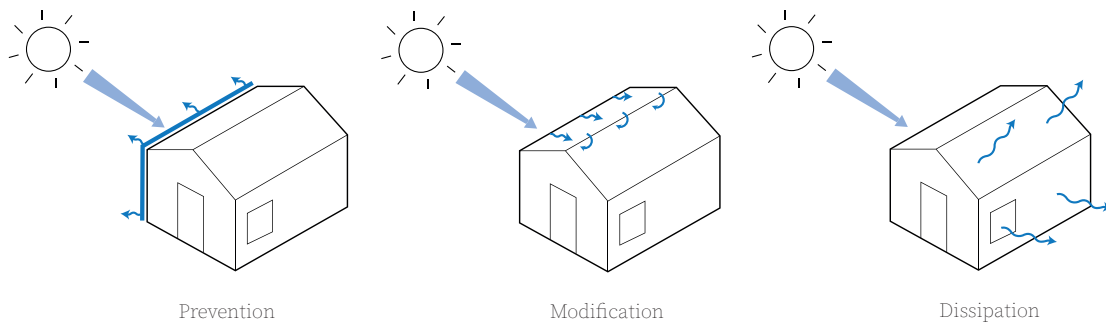


Fig. 2.4: Abstract principles of heat-gain prevention, modification and dissipation. (Author's work)

2. LITERATURE REVIEW

2.2.1 Heat-gain prevention mechanisms

Prevention mechanisms aim to limit the amount of heat entering the building (Fig. 2.5). For cooling-oriented design, these mechanisms determine how much thermal load the building must dissipate later and therefore directly influence both $Q_{cool,annual}$ and $Q_{cool,peak}$. Heat transfer through the glazing by conduction plays a secondary role compared to Q_{solar} , but still contributes to the overall heat balance during warm periods.

For opaque elements this is achieved by reducing conductive heat transfer (Q_{cond}) through the envelope. This is governed by the overall heat transfer coefficient (U), which relates heat flow through a building element to the temperature difference across it. In cooling-dominated periods, low U -values limit heat inflow through walls, roofs and floors and reduce the thermal stress.

Transmission heat gains can be calculated using the transmission heat transfer coefficient (H_t)

which includes all planar elements, linear thermal bridges and point thermal bridges (Van Der Linden et al., 2024; Medved et al., 2022). These parameters are directly controlled by design choices such as façade layout, insulation levels and construction detailing.

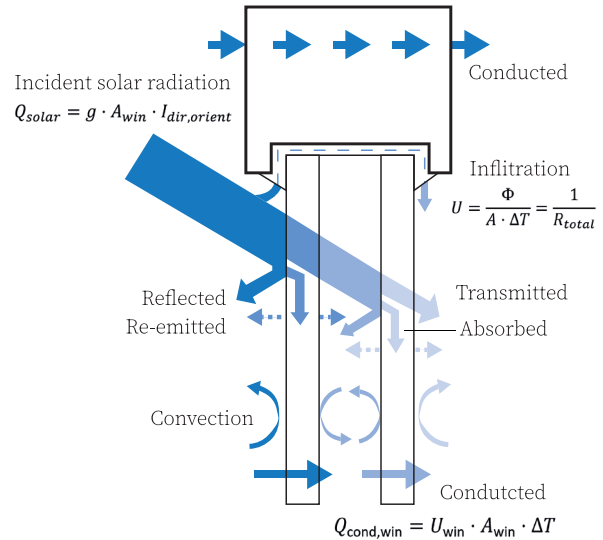
Infiltration forms an additional heat transfer pathway through uncontrolled air movement. Airtight construction reduces this pathway. In the context of passive cooling, this determines whether ventilation heat transfer acts as a cooling potential or becomes an additional heat gain. The infiltration rate is uncertain, as it depends on construction quality. (Van Der Linden et al., 2024).

Orientation and solar exposure

The incident irradiance (I_{dir}) on a building depends strongly on orientation, sun angle and sky conditions. South façades receive predictable high-angle sun, east and west façades receive low-angle morning and evening sun that penetrates deeply and causes higher indoor T_a . Prieto Hoces et al. (2018) show that east- and west-oriented façades in mid-latitude climates experience disproportionately high Q_{cool} due to low-angle solar incidence. Dutch simulation studies similarly show that east-west façades typically dominate overheating hours unless controlled by shading (Raji et al., 2017). Large east- and west-facing window areas therefore create diurnal temperature swings. Lomas and Porritt (2017) report that overheating risk in UK nursing homes and hospitals is strongly orientation-dependent, with east- and west-facing patient rooms posing the greatest risk.

Window-to-wall ratio & glazing type

The window-to-wall ratio (WWR) and glazing type jointly determine the transparent part of the façade and its thermal, solar and visual performance. Their effect is governed by the contrast between glazing and opaque wall elements in terms of U -value, solar transmittance (g or $SHGC$), visible light transmittance (VLT) and interior surface temperature, which also affects radiant comfort. Increasing WWR generally raises $Q_{cool,annual}$ and peak T_{indoor} , while reducing heating demand only marginally (Wu et al., 2021).



The total heat loss is calculated through a wall fragment at a 1 K temperature difference:

$$H_t = H_{glass} + H_{wall} = (A_g \cdot U_g) + (A_w \cdot U_w) = A_{total} \cdot \bar{U}_{outside\ wall}$$

Fig. 2.5: Abstract window cross-section showing heat-gain prevention mechanisms, Eqs. 3–6. Adapted and redrawn from Van Der Linden et al. (2024).

2. LITERATURE REVIEW

Glazing type modifies this balance through the U -value, g -value and VLT . Modern low-emissivity insulated glazing can reduce Q_{cond} while still allowing daylight and solar transmission (Van Der Linden et al., 2024). In temperate climates, studies indicate that for highly glazed façades, reducing the g -value has a stronger effect on cooling demand and overheating than further U -value optimisation (Raji et al., 2017; Raji et al., 2019; Wu et al., 2021). However, very low g -values may reduce daylight availability and visual comfort, making glazing selection a trade-off between cooling reduction, radiant comfort and daylight performance.

External shading

External shading reduces the effective solar transmittance of the façade without altering the glazing itself. Horizontal overhangs block high summer sun, while vertical fins limit low-angle morning and evening sun (Van Der Linden et al., 2024). Because solar energy is blocked before it enters the glazing, external shading is more effective than internal shading in limiting heat gains. Prieto Hoces et al. (2018) show that in mid-latitude climates external shading can reduce $Q_{cool,peak}$ by 40–65%, with the strongest effects on east- and west-facing façades. Dutch simulation studies similarly identify shading as one of the most effective passive measures for reducing overheating (Raji et al., 2017; Raji et al., 2019). This is also confirmed by nursing-home studies in Cfb climates (Lomas & Porritt, 2017; Porritt et al., 2012).

2.2.2 Heat-gain modification mechanisms

Modification mechanisms do not primarily reduce heat gains, but alter the way a building responds to thermal loads over time. These mechanisms influence peak temperatures, temperature fluctuations and the timing of heat release and are shown conceptually in Fig. 2.6 (Konstantinou & Prieto Hoces, 2018).

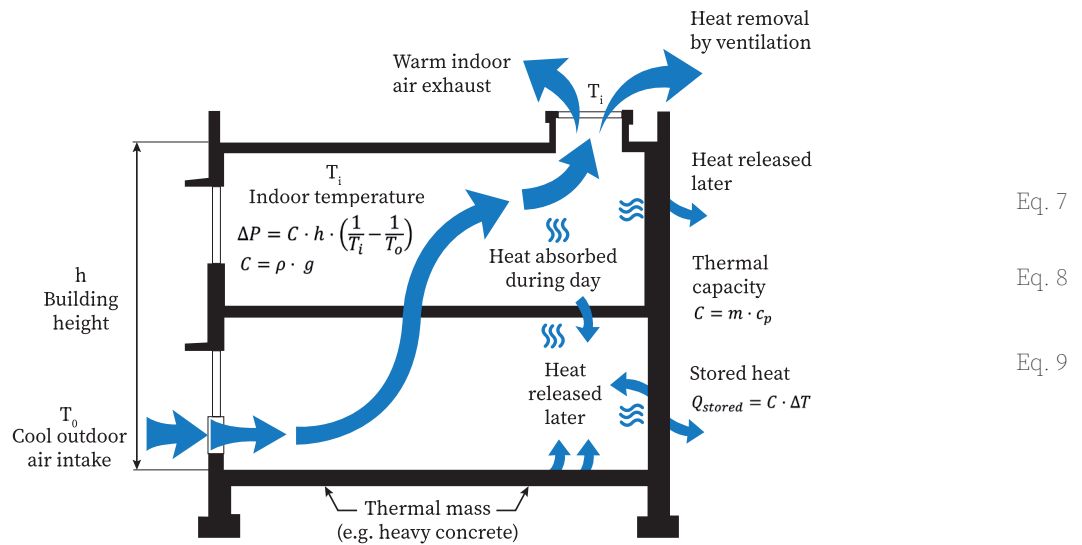


Fig. 2.6: Simplified schematic overview of heat-gain modification in a building section. (Author's work)

Thermal mass

Thermal mass refers to the capacity of building materials to store and release heat. This capacity is quantified by thermal capacitance, which depends on material density and specific heat capacity and determines the extent to which materials buffer short-term thermal loads (Medved et al., 2022). Its dynamic effect is commonly described through time lag and decrement factor, indicating the delay and reduction of temperature peaks. Thermal mass does not remove heat gains, but redistributes them over time, reducing peak loads only when combined with effective heat dissipation mechanisms (Konstantinou & Prieto Hoces, 2018; Maghami et al., 2025).

2.2.3 Heat-gain dissipation mechanisms

Heat dissipation encompasses all methods of removing heat and transferring it to another location (often the exterior).

Convective heat dissipation

Convective heat dissipation removes indoor heat by replacing or redistributing warm air through ventilation. In passive cooling, this is mainly governed by natural ventilation, driven by wind-induced pressure differences across the façade and buoyancy forces caused by indoor–outdoor temperature differences. Fig. 2.7 illustrates this principle.

Wind-driven ventilation occurs when external wind pressures force air through openings in the building envelope. The resulting airflow rate depends on wind speed, opening area and discharge coefficients, which are affected by early-stage design parameters such as building orientation, façade porosity and window configuration.

Buoyancy-driven ventilation, or stack flow, results from density differences between warm indoor air and cooler outdoor air. The driving pressure depends on the vertical separation between openings and the indoor–outdoor temperature difference (Allard & Santamouris, 1998). The volumetric airflow rate can be approximated by Eq. 11:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

Eq. 11

where Q is the airflow rate, C_d the discharge coefficient, A the opening area, ΔP the pressure difference across the opening, and ρ the air density. For stack-driven ventilation, ΔP is related to the temperature difference and height difference between openings. High- and low-level openings can therefore increase stack potential, but this mechanism weakens during heatwaves when indoor–outdoor temperature differences decrease.

Opening and space geometry

Local air movement depends on opening geometry, airflow path, room depth and stratification. Opening area, position and shape influence jet velocity, penetration depth and airflow direction. Constricted openings can increase local velocity through the Venturi effect, while the Coandă effect can guide incoming air along ceilings or walls before it reaches the occupied zone. These principles allow façade design to influence occupant-level cooling rather than only total air exchange (Teng et al., 2025; Aflaki & Jarrahi, 2025).

Room geometry further modifies ventilation effectiveness and thermal exposure. Greater room depth generally reduces air velocity away from façade openings due to jet decay, mixing and flow resistance, while also changing solar penetration and radiant heat gains. At building scale, deep-plan configurations are more weakly coupled to outdoor conditions and may reduce natural ventilation potential, whereas shallow plans support daylight and cross-ventilation but increase façade area and

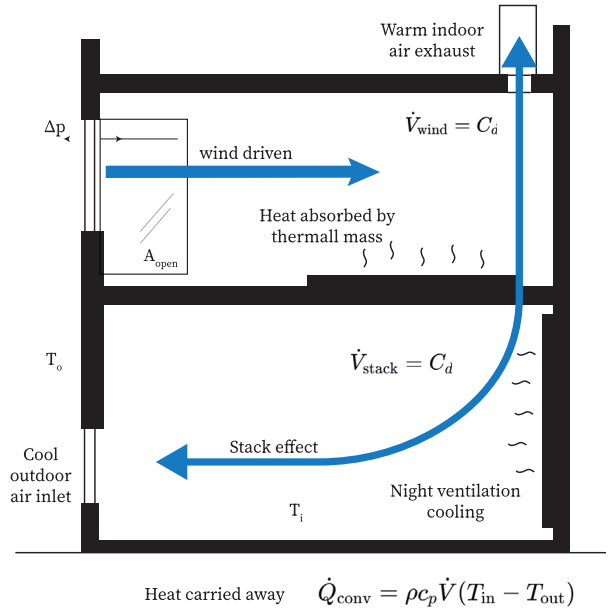


Fig. 2.7: Simplified schematic overview of convective heat dissipation, Eq. 10. (Author's work)

2. LITERATURE REVIEW

transmission heat exchange (Konis et al., 2016; Raji et al., 2019). Building compactness therefore affects the balance between solar exposure, ventilation potential and transmission losses (Maghami et al., 2025).

Ceiling height affects buoyancy-driven airflow and thermal stratification. Higher rooms can increase stack pressure and allow warm air or contaminants to accumulate above the occupied zone, supporting removal through high-level exhaust openings (Hunt et al., 1999). However, excessive stratification may reduce effective air movement at bed level and introduce vertical temperature gradients that conflict with comfort criteria.

Airflow path

In healthcare environments, airflow design must also address infection control. Ventilation rate and air distribution influence contaminant dilution and transport. Shen et al. (2021) estimated that 100% outdoor-air ventilation can reduce airborne infection risk by approximately 27%, although this reduction depends on the specific room and exposure conditions. Airflow is generally recommended from cleaner to less clean zones, while v_{air} around 0.2 m/s may support upward particle transport (Nourozi et al., 2024). Displacement ventilation can reduce infection risk, but may also create particle accumulation near staff breathing height. Filtration requirements, such as staged filtration using MERV 7 followed by MERV 13 or 14 filters, further constrain façade design, airflow paths and the feasibility of fully passive ventilation concepts (ASHRAE et al., 2020).

Besides mean v_{air} , turbulence intensity (TI) affects draught perception and local thermal discomfort. ISO 7730 includes TI in the DR formulation, indicating that higher turbulence levels increase the probability of draught discomfort (Eq. 13). Although this study evaluates elevated v_{air} mainly through mean v_{air} and SET -based comfort indices, turbulence is acknowledged as relevant, particularly for bed-bound patients whose face may remain exposed to airflow.

$$DR = (34 - T_a)(\bar{v} - 0.05)^{0.62}(0.37 \cdot TI \cdot \bar{v} + 3.14) \quad TI = \frac{\sigma_v}{\bar{v}} \quad \text{Eq. 12 and 13}$$

Where TI denotes turbulence intensity, σ_v the standard deviation of local velocity fluctuations, v the local mean air velocity, DR the predicted percentage of occupants dissatisfied due to draught and T_a the local air temperature.

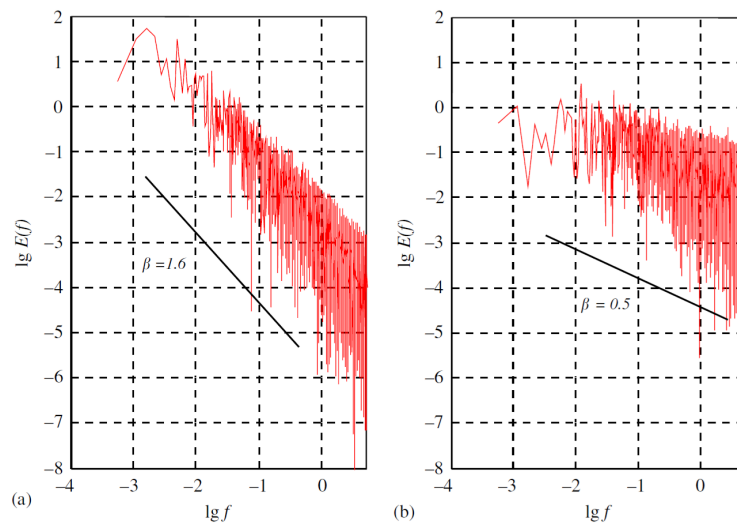


Fig. 2.8: Typical logarithmic power spectrum curves of (a) natural wind and (b) mechanical airflow. Adapted from Q. Ouyang et al. (2006).

Latent heat dissipation (building scale)

Latent heat dissipation refers to cooling mechanisms in which thermal energy is removed through phase change rather than through a temperature difference. In building physics this is most commonly associated with the evaporation of water, whereby sensible heat is converted into latent heat (Medved et al., 2022). Because the latent heat of evaporation of water is very large (approximately 2.5 MJ per kilogram), even small amounts of evaporation can in principle provide significant cooling power (Van Der Linden et al., 2024; Medved et al., 2022). Other latent heat dissipation methods are wetted surfaces, PCM, or evapotranspiration from vegetation. However, the effectiveness of all evaporative processes is strongly dependent on humidity and airflow. At high relative humidity, evaporation rates decrease rapidly, limiting cooling potential (Medved et al., 2022). This makes latent cooling mechanisms highly climate-dependent and generally less reliable in temperate, humid climates such as the Netherlands.

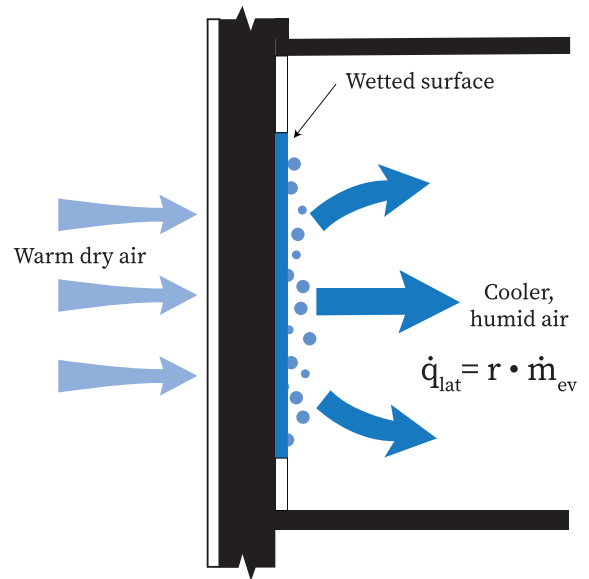


Fig. 2.9: Simplified schematic overview of latent heat dissipation, Eq. 14. (Author's work)

Ground-coupled heat dissipation

Ground-coupled heat dissipation refers to heat transfer from the building to the soil by conduction. Because soil has a large thermal mass and slow temporal temperature variation, it can act as a heat sink during warm periods. Heat transfer occurs either directly through structural contact or indirectly via air or water paths in contact with the ground. Its effectiveness depends on soil properties, moisture content, depth and the duration of heat exchange (Konstantinou & Prieto Hoces, 2018; Maghami et al., 2025).

Radiative sky cooling

Radiative cooling relies on net long-wave radiation from a surface to the sky through the 8–13 μm atmospheric window, in which the atmosphere is relatively transparent (D. Zhao et al., 2019). Under favourable conditions, net cooling powers of 40–80 W/m^2 can be achieved. However, cloud cover, water vapour and parasitic convective and conductive heat fluxes substantially reduce this potential, especially in windy and humid climates such as the Netherlands (D. Zhao et al., 2019).

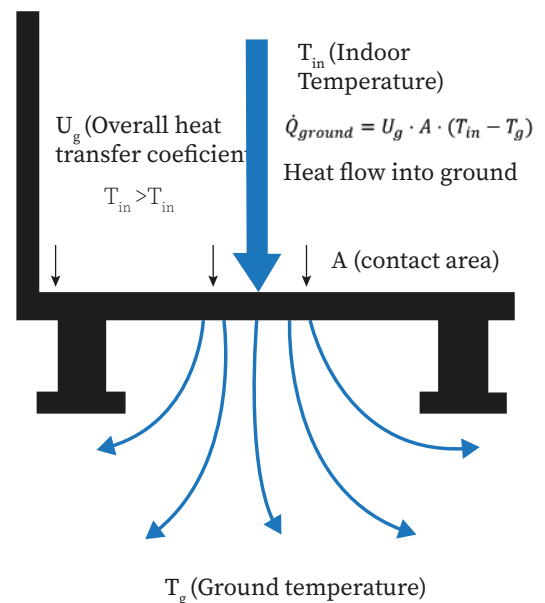


Fig. 2.10 Simplified schematic overview of ground-coupled heat dissipation, Eq. 15. (Author's work)

Hybrid cooling strategies

The literature identifies a grey zone between passive and active cooling. In this research, these approaches are described as low-exergy systems, following Givoni (1994), Kalz and Pfafferoth (2014). Examples include small fans, pumps and radiant panels, which operate with limited energy input and small temperature differences while supporting passive heat exchange mechanisms.

Low-exergy systems are therefore not treated as substitutes for passive strategies, but as supportive measures that can improve their robustness. Electric fans can improve thermal comfort under warm conditions by increasing convective and evaporative heat loss, while radiant panels can stabilise thermal conditions during heatwaves without introducing draught or increasing infection risk (Tang et al., 2022; Hoffmann et al., 2021; Meade et al., 2024). Personalised combinations of ventilation and radiant systems have also shown potential in patient rooms, although their effectiveness depends on spatial configuration and interaction with background ventilation (Yuan et al., 2021).

In healthcare environments, direct occupant control over ventilation is often limited, as windows and ventilation devices may be operated by staff or restricted by safety requirements. Since perceived control can improve thermal satisfaction (Kwon et al., 2018), passive and hybrid strategies must provide predictable airflow conditions while balancing convective cooling against draught risk, particularly for immobile patients with limited adaptive capacity.

Climate dependence of passive mechanisms

Passive heat dissipation mechanisms are strongly climate-dependent. Natural ventilation can reduce annual cooling demand in warm-dry climates, but is less reliable in temperate humid regions and may increase cooling demand in warm-humid conditions due to dehumidification requirements (Prieto et al., 2018). In the Dutch temperate maritime climate, small indoor-outdoor temperature differences during heatwaves, variable wind conditions and high humidity limit the reliability of buoyancy- and wind-driven cooling (Raji et al., 2019; Beck et al., 2018; KNMI, 2023).

Climate change further reduces passive cooling potential by increasing average temperatures, heatwave frequency and night-time temperatures, thereby weakening night ventilation and thermal mass activation (Hamdy et al., 2017; Laouadi et al., 2023). Regional differences remain relevant: coastal locations may benefit from higher wind availability, while inland and urban contexts face stronger overheating peaks and UHI effects (KNMI, 2023).

Well-insulated buildings in moderate climates are increasingly prone to overheating without effective solar control and ventilation strategies (Hamdy et al., 2017). Although future climate projections strongly affect absolute overheating risk, studies indicate that the relative performance ranking of envelope-based solar control measures often remains stable (Zhang et al., 2021; Heiranipour et al., 2025; Liu et al., 2023). In this study, climate is therefore treated as an external boundary condition that affects performance magnitude rather than design hierarchy, represented through a fixed future weather scenario for 2050 instead of probabilistic climate modelling.

Overview of passive strategies

The passive cooling strategies identified in the literature are summarised in Table 2.1. The table provides an overview of relevant applications and mechanisms, but should not be interpreted as an exhaustive classification, as additional forms, combinations and project-specific adaptations remain possible.

2. LITERATURE REVIEW

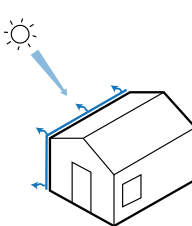
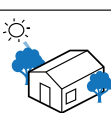
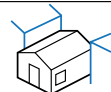
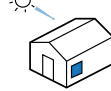
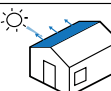
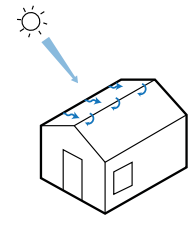
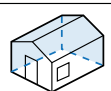
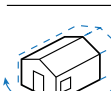
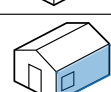
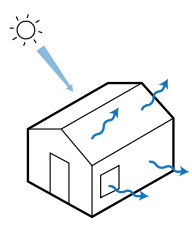
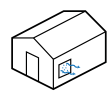
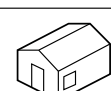
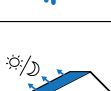
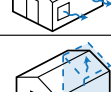
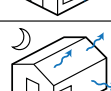
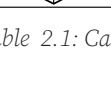
Category		Strategy	Explanation
Prevention 		Deciduous trees	Deciduous trees that provide shade in summer and allow solar radiation in winter.
		Green walls/VFS	Vegetated façade systems that cool façade surfaces through shade, evaporation and additional thermal resistance.
		Green roofs	Vegetation layers on roofs that limit roof warming through insulation, evaporation and thermal mass.
		Pergolas	Light, open structures with vegetation that provide shade while maintaining air movement.
		Cool pavements	Paving with high reflectivity or water permeability that stores less heat and reduces heat stress.
		High albedo surfaces	Surfaces with high reflectivity that reflect solar radiation and thus limit heat storage in urban environments.
		Building spacing	Distance and positioning between buildings that influence solar radiation, wind flow and heat dissipation.
		Shading by buildings	Shading from surrounding buildings that reduces direct solar exposure on facades and outdoor spaces.
		Water bodies	Open water or ponds that lower the ambient temperature through heat storage and evaporation.
		Spectrally selective glazing	Glass with selective spectral transmission that limits solar heat (IR) while allowing daylight to pass through largely unimpeded.
		Solar control glazing	Coated glass that reflects or absorbs part of the solar radiation to reduce heat gains through windows.
		Thermochromic glazing	Glass whose solar heat transmission automatically decreases as the temperature rises, without active control.
		Photochromic glazing	Glass that changes its light and heat transmission under the influence of sunlight intensity.
		Cool walls	Facade finishes with high reflectance that reflect solar radiation and limit facade heating.
		Cool roofs	Roof finishes with high reflectivity and emissivity that reduce heating from solar radiation and promote heat dissipation.
		Ir-Reflective pigments	Pigments in coatings that reflect infrared radiation without requiring visible light colours.
		Overhangs	Fixed horizontal projections above openings that limit direct solar gains by blocking high-angle summer sun.
		Louvers and fins	Vertical/inclined shading elements that reduce solar radiation while preserving daylight access and outward view.
		Lightshelves	Horizontal reflective surfaces redirect daylight deeper into the interior while shading the lower part of window.
		Perforated screens	Porous façade layers that attenuate solar radiation and glare while allowing airflow and partial visual permeability
Modification 		High emissivity ceilings	Interior finishes with high heat radiation emission that release stored heat more efficiently into the room.
		Selective absorbing surfaces	Surfaces that absorb targeted solar radiation and store heat in a controlled manner instead of reflecting it.
		Low mass finishes	Light interior finishes with low thermal mass that respond quickly to temperature fluctuations and store little heat.
		Recessed facades	Facade surfaces that are set back from the building mass, creating self-shading and limiting direct solar radiation.
		Stepped facade	Facade shape with staggered floors that increases shading and reduces solar load per floor.
		Compactness ratio	The ratio between building volume and façade surface area, which determines how much heat is exchanged with the outside air.
		Orientation & WWR	The positioning of the building in relation to the sun, which controls solar gains and loads.
		Balconies as buffers	Outdoor spaces that act as a thermal transition zone and reduce direct sunlight and heat entering the interior.
		Asymmetric shaping	Spatial design in which volumes are formed unevenly to control solar load and air flow.
		Room depth	The distance between facades within a space that determines how deeply sunlight and heat penetrate.
		Thermal zoning	The division of spaces based on use and heat load to limit internal heat flows.
		Ceiling height	The vertical dimension of a space that influences heat stratification and thermal comfort.
		Winter garden/buffer	Semi-conditioned transition space that captures solar heat and dampens temperature fluctuations between inside and outside.
		Double skin facade	Facade system with two shells and a ventilated cavity that combines solar load, heat dissipation and insulation.
		Ventilated facade	Facade construction with an open air layer that dissipates heat from solar radiation before it reaches the interior.
		Stone floors	Heavy floor finish that absorbs heat during the day and releases it slowly into the space.
		Masonry mass	Solid building components made of stone-like material that buffer thermal fluctuations through heat storage.
		Exposed concrete	Load-bearing or finishing concrete elements that actively contribute to heat storage and release.
		Latent heat plaster	Finishing layer with phase transition material that temporarily stores heat during melting, thereby smoothing out peak temperatures.
Dissipation 		PCM's	Materials that store heat via a phase transition at a specific temperature and release it again later.
		Thermochemical storage	Storage system that captures heat via reversible chemical reactions for long-term, season-independent buffering.
		Wetted pads	Moistened filter elements through which air flows and cools down through water evaporation.
		Porous ceramic facades	Facade panels made of porous ceramic that retain water and reduce surface temperatures through evaporation.
		Water films	Thin layer of water over a surface that dissipates heat through evaporation and increased heat transfer.
		Shaded water surfaces	Water elements that contribute to local air and radiation temperature reduction through shade and evaporation.
		Passive cooling towers	Vertical towers that allow warm air to rise and cool through evaporation before it enters the space.
		Earth berming	Earth covering of facades/building components with soil to dampen temperature fluctuations through thermal mass.
		Ground-air exchanger	Ventilation system that directs outside air through the ground so that it enters the space pre-cooled.
		Basement cooling chambers	Underground spaces that utilise cool ground temperatures to dissipate heat from above-ground zones.
		Earth ducts	Underground air ducts that thermally condition air through heat exchange with the ground.
		Spectral-selective membranes	Thin membranes that reflect specific wavelengths and maximise heat emission to the sky.
		Radiative roof panels	Roof surfaces that actively radiate heat to the sky, especially effective on clear nights.
		Roof ponds	Water basins on the roof that absorb heat and release it at night through evaporation and radiation.
		Photonic materials	Advanced materials that selectively emit heat in the infrared spectrum and limit solar radiation.
		High-emissivity roofs	Roof finishes with high heat radiation capacity that release heat to the environment more quickly.
		Single sided ventilation	Ventilation via a single façade where air flows in and out due to pressure differences and turbulence.
		Cross-ventilation	Cross ventilation where air flows through opposite façade openings under the influence of wind pressure.
		Wind catchers	Roof or façade structures that catch the wind and actively draw air into the building.
		Solar chimneys	Vertical shafts that heat up due to solar radiation, creating natural draughts for air renewal.
		Atrium stack	Atrium space that acts as a vertical chimney and removes warm air via stack effect.
		Thermal stack	Vertical air flow driven by temperature differences between low and high openings in the building.
		Secure vents	Lockable ventilation openings that allow air to flow in without compromising security or creating a risk of break-ins.
		Night flushing	Night-time ventilation, using cool outside air to remove heat that has built up in structures and rooms.

Table 2.1: Categorisation and explanation of individual passive cooling strategies. (Author's work)

2.3 Physiological heat balance of human body and thermal comfort

Thermal comfort describes occupants' perception of the thermal environment and is defined as "the condition of mind which expresses satisfaction with the thermal environment" (Fanger, 1970). This definition underpins widely used standards such as ISO 7730 and ASHRAE Standard 55. In this study, thermal comfort literature is used to define simulation criteria and user profiles for healthcare environments, where thermal perception may differ substantially between staff, mobile patients and immobile patients.

In the Netherlands, the Besluit Bouwwerken Leefomgeving (BBL) defines minimum legal requirements for indoor environmental performance, but these thresholds do not necessarily ensure acceptable conditions for vulnerable healthcare occupants. European and Dutch guidance for elderly or vulnerable users is primarily provided by organisations such as CEN, WHO and REHVA, and by the Programma van Eisen Gezond Binnenklimaat Langdurige Zorg and its underlying studies (Boerstra et al., 2021; Boerstra et al., 2024). Current requirements are often expressed through indoor T_a and exceedance hours, while healthcare-specific comfort evidence, particularly for differences between vulnerable occupant groups, remains limited compared with offices, housing and schools (Bouzidi et al., 2021). Appendix D summarises temperature recommendations from relevant organisations and studies.

A distinction is required between thermal comfort and thermal neutrality. Thermal comfort refers to subjective satisfaction with the thermal environment, whereas thermal neutrality describes a physiological heat balance between the body and its surroundings (Zhao et al., 2020). Although both conditions may coincide, occupants can experience comfort despite small deviations from thermal neutrality.

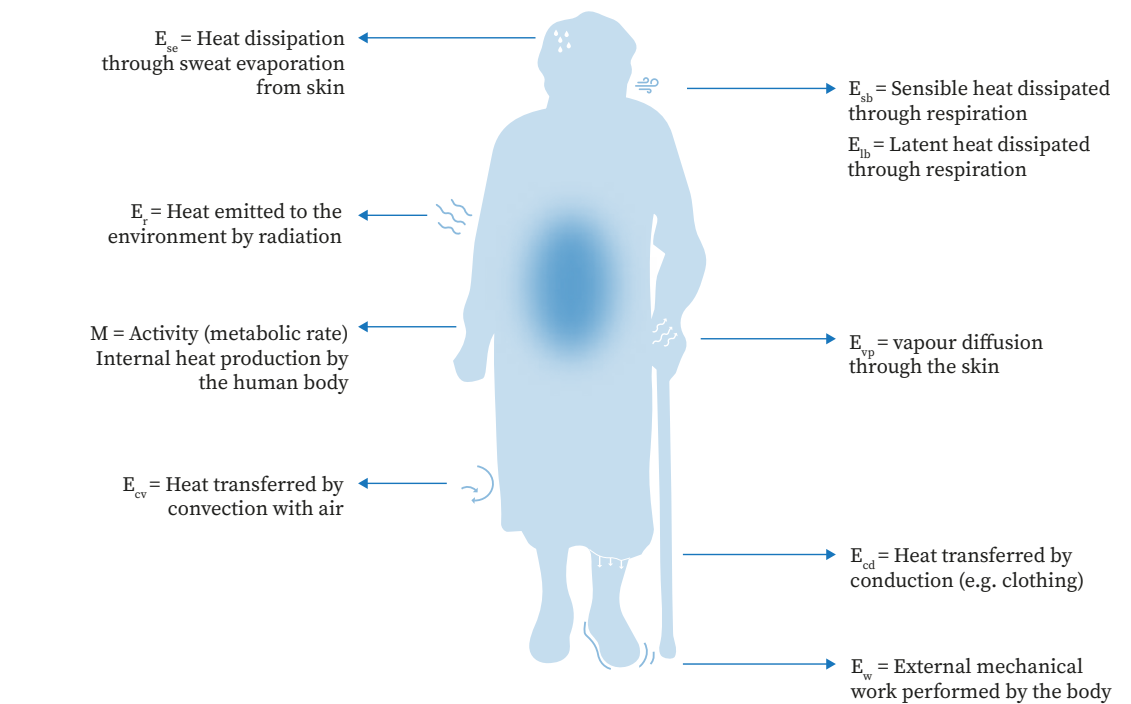
Thermal comfort results from the interaction between environmental conditions and the human heat balance. The following section therefore discusses how the body exchanges heat with its environment and how air temperature (T_a), mean radiant temperature (T_r) and air velocity (v_{air}) influence thermal perception.

2.3.1 Physiological heat balance of human body

Humans maintain core body temperature within a narrow range around 36.5 °C by balancing metabolic heat production with environmental heat exchange (Zhao et al., 2020). Heat is transported from the body core to the skin through blood circulation and dissipated at the skin surface through radiation, convection, evaporation and, to a lesser extent, conduction (Zhao et al., 2020). These mechanisms are commonly represented by the steady-state human heat balance equation shown in Fig. 2.11. Where M is metabolic heat production, W is mechanical work, E is evaporative heat loss, C is convective heat loss, R is radiative heat loss, P_a ambient water vapour pressure, and T_a the air temperature. In comfort conditions, the body is assumed to be in steady state.

Within typical Dutch indoor humidity ranges of 30–70%, humidity generally has less influence on thermal sensation than T_a , mean T_r and v_{air} . However, it remains physiologically relevant because it affects evaporative heat loss and is therefore included in heat-balance models. Together with clothing insulation (CLO) and metabolic rate (MET), these environmental parameters form the basis of most thermal comfort models used in building performance analysis (Fanger, 1970).

2. LITERATURE REVIEW



$$\underbrace{(M - W)}_{\text{net heat to be dissipated}} = C + R + \underbrace{3.05[5.733 - 0.007(M - W) - P_a]}_{\text{latent heat loss through skin diffusion}} + \underbrace{0.42(M - W - 58.2)}_{\text{Regulated sweating}} + \underbrace{0.0173M(5.867 - P_a)}_{\text{Latent heat loss through respiration.}} + \underbrace{0.0014M(34 - t_a)}_{\text{Sensible heat loss through respiration.}}$$

Equation 18

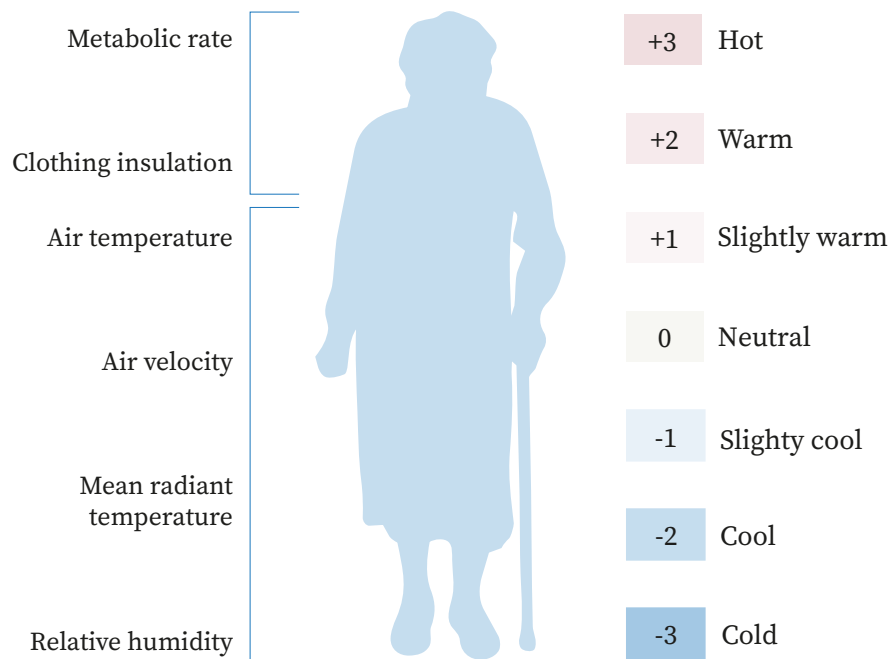


Fig. 2.11: Human heat balance & Fanger parameters. (Author's work)

Heat balance of vulnerable occupants

Rising ambient temperatures activate vasodilation and increase skin blood flow to support heat dissipation. Prolonged heat exposure can therefore increase cardiovascular strain, particularly for occupants with reduced thermoregulatory capacity (Zhao et al., 2020).

Vulnerable occupants may have an altered heat balance due to ageing, chronic illness or medication use, which can reduce sweating efficiency, vasodilatory response and cardiovascular reserve (Meade et al., 2020; Yu Tian, 2023). Consequently, heat stress thresholds may be reached earlier than predicted by standard comfort models developed for healthy adults (Boerstra et al., 2023).

For bed-bound patients, bedding and limited movement further modify heat exchange. Zhang et al. (2020) therefore proposed an adapted heat balance formulation for hospital inpatients, incorporating patient-specific MET and the total thermal resistance of the body-bedding system. For lying patients, this total resistance (R_T) includes CLO , bedding effects and posture-dependent body coverage. The modified heat balance equation is defined as:

$$M - W = \frac{1}{R_T} [(t_{sk,req} - t_o) + 3.762(p_{sk,s} - p_a)] + 0.0014M(34 - t_a) + 0.0173M(5.87 - p_a) \quad \text{Eq. 14}$$

With required mean skin temperature: $t_{sk,req} = 35.7 - 0.0275(M - W)$ Eq. 15

Rather than adopting fixed MET values from ISO 7730, metabolism can be estimated using resting energy expenditure (REE) and physical activity level (PAL). REE represents baseline heat production at rest, while PAL expresses total energy expenditure relative to REE . Typical PAL values range from approximately 1.2 for bedridden occupants to 2.0 or higher for physically active individuals (Zhang et al., 2020).

$$REE = 629 - (11 \times AGE) + (25 \times G) - (609 \times OB) \quad OB = \begin{cases} 1 & \text{if BMI} > 30 \\ 0 & \text{else} \end{cases} \quad \text{and } BMI = \frac{G}{l^2} \quad \text{Eq. 16}$$

$$TEE = REE \times PAL \quad M = \frac{TEE}{A_D} \quad \text{Eq. 17, 18}$$

For lying patients, the operative temperature can then be expressed as:

$$t_o = t_{sk,req} + 3.762(p_{sk,s} - p_a) - R_T(M - C) \quad \text{Eq. 19}$$

where the convective heat exchange term is expressed as:

$$C = 0.0014M(34 - t_a) + 0.0173M(5.87 - p_a) \quad \text{Eq. 20}$$

Eq. 19 and 20 show that the T_o required for thermal neutrality depends on the total thermal resistance R_T . When R_T is underestimated, the term $R_T(M - C)$ becomes too small and the predicted T_o may approach skin temperature values of approximately 34–35 °C, which is unrealistic for indoor environments. A practical plausibility condition is therefore required:

$$R_T(M - C) > 3.762(p_{sk,s} - p_a) \quad \text{Eq. 21}$$

2. LITERATURE REVIEW

If this condition is not met, evaporative heat transfer dominates the heat balance and the predicted T_o becomes physically inconsistent (Zhang et al., 2020). This is relevant because patient-specific thermal neutrality can be derived from actual MET and bedding resistance rather than standard sedentary assumptions. Zhang et al. (2020) show that small metabolic differences already affect neutral T_o : for example, a lying patient with 1.9 CLO and $M=40 \text{ W/m}^2$ has a neutral T_o of 24.8°C , approximately 0.5°C lower than a healthy sleeper under the same insulation conditions.

Older adults are also more sensitive to cold surfaces and radiant asymmetry, particularly near poorly insulated or sun-exposed façades (Boerstra et al., 2021). Although reported comfort temperatures for elderly users vary, studies consistently indicate a preference for warmer and more stable conditions than for staff or healthy adults (Yuan et al., 2021; Tartarini et al., 2018).

For bedridden patients, bedding and posture substantially affect heat dissipation. Zhang et al. (2020) show that the total thermal resistance of the patient–bed system limits convective and radiative heat loss, even at low MET values. As illustrated in Fig. 2.12, T_o requirements therefore differ between seated and bed-bound occupants, making bedding configuration an important parameter in patient-specific thermal comfort assessment.

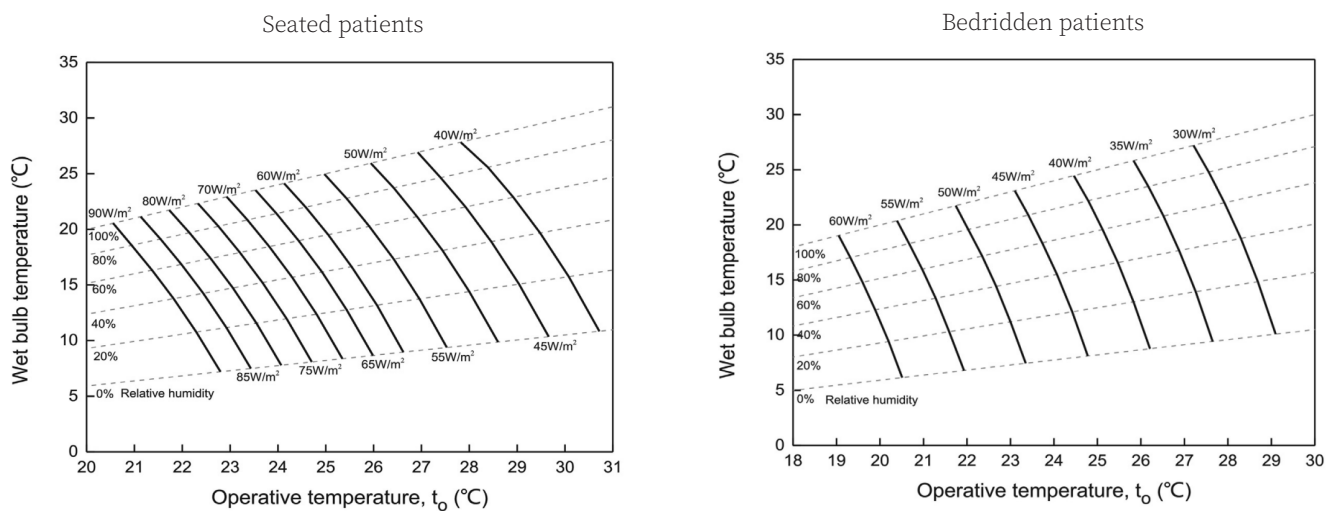


Fig. 2.12: a. Comfort diagrams for seated patients in summer (0.6clo , airspeed $\leq 0.15 \text{ m/s}$). b. Comfort diagrams for lying patients in summer (1.9clo , airspeed $\leq 0.15 \text{ m/s}$) (H. Zhang et al., 2020).

Ruggiero et al. (2022) demonstrate this limitation in a case study comparing north- and south-facing hospital patient rooms in Italy. Although indoor temperatures remained within the conventional ISO 7730 summer comfort range of approximately $24.5^\circ\text{C} \pm 1.5^\circ\text{C}$, more than 50% of the calculated PMV values for bedridden patients fell outside the proposed comfort zone. This indicates that temperature compliance alone does not ensure thermal comfort for hospitalised patients, particularly in rooms with high solar exposure.

Conventional temperature-based control is therefore insufficient for patient rooms. Thermal discomfort may result from an imbalance in patient-specific heat exchange rather than elevated T_a alone.

Non-uniform thermal environments

Thermal comfort and thermal neutrality may diverge in spatially non-uniform environments, where local air movement, radiant asymmetry and vertical temperature gradients challenge the homogeneous conditions assumed in most comfort models. Solar radiation is a key source of such variability, requiring distinction between long-wave radiation from surrounding surfaces and short-wave solar radiation transmitted through glazing (Hodder & Parsons, 2006). Direct solar exposure can substantially increase occupant-level radiant heat load; experimental studies show that an additional radiant exposure of approximately 200 W/m² can shift thermal sensation by about one scale unit (Hodder & Parsons, 2006).

Passive and hybrid cooling strategies can also create non-uniform conditions. Natural ventilation produces location-dependent air velocities, displacement ventilation may generate vertical temperature gradients, and radiant systems can introduce surface temperature asymmetry. While limited non-uniformity may improve perceived comfort, thermal sensation can deviate from predictions based on uniform heat-balance models (Zhang et al. 2020; Schellen et al., 2013). Schellen et al. (2013) reported significant differences between model predictions and subjective responses under passive convective cooling, indicating that local conditions affect comfort beyond averaged environmental parameters. Because uniform indoor conditions cannot satisfy all healthcare users equally, micro-climatisation and individual comfort systems may provide an important complementary strategy.

2.3.2 Influence of elevated air speed on human body heat balance

Elevated v_{air} affects the human heat balance by increasing convective and evaporative heat exchange between the body and its environment. Convective heat loss is governed by the convective heat transfer coefficient, which increases with v_{air} : ($h_c \propto \sqrt{v_a}$). As v_{air} rises, heat transfer from the clothing or skin surface to the surrounding air increases, improving sensible heat dissipation without necessarily reducing indoor T_{air} .

Air movement also supports evaporative cooling. Through the Lewis relation, evaporative heat loss is linked to the evaporative heat transfer coefficient:

$$C = h_c(T_{cl} - T_a) \quad E = w_{he}(p_{sk,sat} - p_a) \quad h_e = 16.5 h_c \quad \text{Eq. 22, 23, 24}$$

Where w is skin wettedness and h_e the evaporative heat transfer coefficient. Since h_e is coupled to convective heat transfer, increased v_{air} enhances sweat evaporation and can reduce T_{sk} and physiological heat strain. Air movement therefore does not primarily cool the space, but extends the range of ambient conditions under which occupants can maintain thermal comfort.

Controlled experiments show that higher v_{air} values can reduce thermal dissatisfaction, particularly at elevated temperatures (Song et al., 2021). In occupant-controlled environments, increased v_{air} may raise the upper acceptable T_o by approximately 2 °C. However, most evidence is based on climate chamber studies with healthy adults under uniform conditions, limiting direct transferability to healthcare environments. Table 2.2 gives a brief comparison of different studies on increased v_{air} and T_o .

ASHRAE 55 therefore distinguishes between spaces with and without occupant control over air movement. Higher v_{air} values are allowed when occupants can adjust v_{air} , whereas non-controlled environments are limited by SET-based criteria dependent on T_o . This distinction is critical for passive ventilation, where air movement is often determined by façade design and outdoor conditions.

2. LITERATURE REVIEW

Study	Air supply device	Air speed range (m/s)	Acceptable operative temperature (°C)	Key implication
Tanabe (1987, 1989)	Wind box	0.3 – 1.6	26.3 – 31.3	Higher air speed extends upper comfort temperature
Rohles (1983); Scheatzle (1989)	Ceiling fan	~1.0	28 – 29.5	Ceiling fans allow comfort at higher temperatures
Ji (2003)	Ceiling fan	0.2 – 0.7	27.1 – 30.1	Moderate air movement improves warm comfort
Chow (2010)	Tower fan	0.5 – 3.0	25.9 – 30.4	Wide velocity range increases acceptable temperature band
Pasut (2014); Zhai (2015)	Ceiling fan	0.1 – 1.2	26 – 30	Elevated air speed compensates for higher indoor temperature
Huang (2013)	Floor fan	0 – 2.0	28 – 32	Strong air movement substantially increases comfort temperature
He (2018)	Desk fan	1.5 – 2.3	26 – 30	Local airflow enables comfort without lowering setpoint
Zhao (2023)	Floor fan	0 – 1.6	26.3 – 31.3	Acceptable temperature increases progressively with velocity

Table 2.2: Comparative overview of studies investigating the relationship between elevated air velocity and acceptable operative temperature. (partly adapted from Zhou et al. (2023))

2.3.3 Thermal comfort models

Several thermal comfort models have been developed to predict occupants' perception of indoor environments. This section reviews the models most relevant to passively cooled healthcare settings, where assumptions regarding activity, clothing and control are critical.

Yuan et al. (2021) reviewed 170 healthcare studies and found substantial variation in applied comfort metrics, including PMV (19%), TSV (16%), operative temperature (14%), PPD (10%) and other indices (41%). This indicates that no single model is universally used for healthcare environments. Moreover, model selection can substantially affect estimates of overheating and energy-saving potential, as also shown for natural ventilation assessments by Prieto et al. (2018). Comfort model choice and underlying assumptions must therefore be explicitly justified.

Conventional comfort models may also underestimate discomfort in healthcare settings, as patients often differ from the healthy adult populations on which these models are based (Bouzidi et al., 2021; Larriva et al., 2022).

PMV/PPD (ISO 7730, ASHRAE 55)

The Predicted Mean Vote (PMV) model is based on the steady-state human heat balance and expresses the imbalance between metabolic heat production and environmental heat loss on a seven-point thermal sensation scale (Fanger, 1970). It predicts the average thermal sensation of a large group of healthy occupants as a function of CLO , T_a , T_r , v_{air} , p_a and MET . The associated Predicted Percentage Dissatisfied (PPD) is subsequently derived from PMV (Fanger, 1970). Both formulas are in Appendix C.

Within the PMV framework, long-wave radiation from surrounding surfaces and short-wave solar exposure are represented through a spatially averaged T_r , with solar radiation typically translated using effective radiant field (ERF) calculations. PMV therefore assumes a homogeneous thermal environment and does not explicitly resolve local radiant asymmetry, draught or vertical temperature gradients; these are treated separately in standards such as ISO 7730 and ASHRAE 55.

Air velocity enters PMV primarily through the convective heat transfer coefficient. However, the classical formulation only partly captures the additional evaporative cooling potential of elevated v_{air} under warm conditions. ASHRAE 55 therefore includes an elevated v_{air} allowance, recognising that higher air velocities can offset higher T_o values and extend the acceptable comfort range.

SET (standard effective temperature)

SET is based on the two-node thermophysiological model by Gagge, which represents the body as a core and skin compartment (Gagge et al., 1971):

$$C_{core} \frac{dT_{core}}{dt} = M - W - H_{core \rightarrow skin} \quad C_{skin} \frac{dT_{skin}}{dt} = H_{core \rightarrow skin} - E - C - R \quad \text{Eq. 25}$$

Heat is transferred between these compartments and exchanged with the environment through convection, radiation and evaporation. SET is defined as the T_{air} in a reference environment, typically at 50% RH and low v_{air} , that produces the same T_{sk} and sweat rate as the actual environment.

Compared with PMV, SET is more sensitive to elevated v_{air} because it explicitly accounts for evaporative heat loss through sweating. However, as with PMV, spatially non-uniform radiation or airflow must be simplified into representative input values, meaning that local discomfort phenomena are not directly predicted. Recent literature suggests that a SET of 28 °C may indicate an upper limit for safe thermal exposure under standardised conditions, although further validation is required (Huizenga et al., 2024). This value should therefore be interpreted as a potential heat-stress threshold rather than a comfort temperature.

Adaptive comfort model

The adaptive comfort model is empirically derived and relates indoor comfort temperature to recent outdoor climatic conditions rather than to a physiological heat balance (de Dear et al., 1998; van Paassen, 2004; Larriva et al., 2022).

$$T_{comfort} = 0.31 T_{out,mean} + 17.8 \quad \text{Eq. 26}$$

Acceptable temperature bands are defined around a neutral T_o , assuming that occupants can adapt behaviourally and psychologically to outdoor conditions. Its applicability to healthcare environments is therefore limited, particularly for sedentary, dependent or bed-bound occupants with restricted adaptive capacity. Air velocity and radiant exposure are treated only indirectly, while spatial non-uniformity and local discomfort are not explicitly addressed. The model is therefore less suitable for assessing patient-room comfort under passive or hybrid cooling scenarios.

Thermal sensation vote (TSV)

Thermal Sensation Vote (TSV) is an empirical comfort indicator based on subjective responses on the ASHRAE seven-point scale (Fanger, 1970). Unlike calculated heat-balance models, TSV reflects perceived thermal state and can therefore include lived responses to draught, solar patches, stratification and other non-uniform effects.

However, TSV cannot be derived directly from simulations without experimental or field-study calibration. It is therefore not used as a primary metric in this research, which relies on predictive simulation. Moreover, subjective sensation does not necessarily indicate physiological strain, and comparisons with PMV show increasing divergence at elevated v_{air} because PMV only partly captures evaporative cooling under warm conditions.

Differentiation in model outcomes

Ruggiero et al. (2022) assessed thermal comfort in hospital environments while accounting for bedding, CLO and reduced patient activity. For conditions with less than 20% dissatisfied occupants, they identified acceptable temperature ranges of approximately 21.8–27.9 °C for patients, 22.0–27.1 °C for visitors and 24.1–25.6 °C for medical staff. Their findings indicate that PMV alone may be insufficient for hospital settings, as patient comfort can also be affected by psychological expectations and contextual factors.

2. LITERATURE REVIEW

They therefore applied a broader adaptive approach than ASHRAE 55 to define upper and lower temperature limits:

$$\begin{aligned} T_{up} &= 0.11 T_{pma} + 23.95 \\ T_{low} &= 0.11 T_{pma} + 18.95 \end{aligned} \quad \text{Eq. 27}$$

Where T_{pma} represents the running mean outdoor temperature over the previous 30 days. Derks et al. (2018) found that nurses in hospital wards often perceived typical indoor temperatures of 20–25 °C as slightly warm, with reported reductions in work performance. The calculated neutral temperature for nursing staff was approximately 21.8 °C, while temperatures approaching 24–25 °C were associated with increased dissatisfaction. These studies show that patients and staff may require different thermal conditions due to differences in activity level, exposure duration and adaptive capacity. Derks et al. (2018) therefore propose zonal conditioning in hospital wards, with warmer patient rooms and cooler staff-dominated or circulation areas.

2.4 LITERATURE REVIEW SUB-CONCLUSIONS

The reviewed literature shows that thermal comfort in hospital patient rooms cannot be assessed reliably through air temperature or cooling demand alone. Healthcare-specific studies indicate that comfort assessment depends on the selected comfort model, the assumed user profile and the distinction between patients and staff. Yuan et al. (2021) show that healthcare studies apply a wide range of indicators, including PMV, TSV, T_o and PPD. This supports the multi-metric approach used in this research, combining T_a , T_o , SET, local v_{air} and user-specific assumptions for MET, CLO and bedding insulation.

The strongest patient-specific evidence is provided by Zhang et al. (2020) and Ruggiero et al. (2022). Zhang et al. (2020) show that bedridden patients require a different heat-balance approach because reduced activity, lying posture and bedding insulation affect heat dissipation. Ruggiero et al. (2022) further demonstrate that patient rooms can remain within conventional ISO 7730 summer temperature ranges while a substantial share of calculated PMV values for bedridden patients falls outside the proposed comfort zone. Temperature compliance is therefore not sufficient as a proxy for patient comfort.

The literature also shows that patients and staff may require different thermal conditions. Ruggiero et al. (2022) report different acceptable temperature ranges for patients, visitors and medical staff, while Derks et al. (2018) found that nurses may already perceive typical ward temperatures of 20–25 °C as slightly warm. This supports an occupant-differentiated evaluation instead of a single zone-average comfort assessment.

Ventilation-driven air movement is relevant because increased v_{air} can improve convective and evaporative heat loss without necessarily reducing indoor T_a . Studies on elevated v_{air} indicate that fans and local airflow can increase acceptable T_o ranges under warm conditions. However, most evidence is based on healthy adults in controlled settings, so its transferability to vulnerable hospital patients remains uncertain. SET is therefore used to assess air-speed effects, while the interpretation remains cautious for bedridden or clinically restricted users.

These findings define the simulation framework used in the following chapters. Solar-control measures are assessed as heat-gain prevention strategies, while natural ventilation and local air movement are assessed as heat-dissipation and occupant-cooling mechanisms. The discussion should return to three literature-based issues: whether temperature-based indicators underestimate discomfort for bedridden patients, whether passive and hybrid strategies affect patients and staff differently, and whether SET provides a defensible but simplified representation of air-speed effects in patient rooms.

3

CASE STUDY DESCRIPTION

This chapter defines the case study used to evaluate passive and hybrid cooling strategies. It describes the healthcare context, selected patient room type and relevant spatial, functional and technical requirements. These parameters form the boundary conditions for the simulation model, including geometry, user profiles, internal loads, ventilation assumptions and comfort criteria, and translate the theoretical framework into simulation scenarios.

3. CASE STUDY DESCRIPTION

3.1 Case study description - Erasmus MC SPOT

A Dutch hospital extension in the schematic design phase is used as representative case study. This phase provides a suitable context for analysing early-stage passive cooling performance, as key parameters such as façade composition, WWR, solar control, and ventilation concept remain adjustable. While the main building volume and preliminary floor plans have been defined, façade detailing and spatial dimensions are still under development and can therefore be treated as design variables.

The case study concerns the Erasmus MC expansion on the southwest side of the existing complex, forming part of the wider 2050 masterplan (Appendix E). The new patient wing accommodates several healthcare functions, including psychiatry and the relocated Sofia Children's Hospital. The building follows a systematic 12-storey structure with a maximum height of approximately 45 m. A representative low-risk inpatient area on level 6 was selected, containing standard patient rooms. The façade is oriented southwest towards 's-Gravendijkwal and has largely unobstructed exposure, with limited nearby obstruction from surrounding buildings (Fig. 3.1 and 3.2).

A preliminary climate analysis was conducted using morphed 2050 EPW weather data from Heiranipour et al. (2024), based on De Bilt measurements (Appendix F). The dataset contains 246 annual hours above 25 °C, a peak outdoor temperature of 34.2 °C, an annual mean temperature of 12.8 °C and a mean RH of 78.6%. During summer daytime hours (June until August), the average outdoor temperature is 22.4 °C, with approximately 55 cooling degree days above 23 °C. At the scale of building performance simulation, differences between De Bilt and Rotterdam are considered acceptable for regional climate representation. However, the dense urban setting may locally increase overheating risk through UHI effects.

Site-specific data from Atlas Leefomgeving indicate an average UHI intensity of approximately +1.8 °C, moderate air pollution levels (8 µg PM_{2.5}/m³ and 20 µg NO₂/m³), environmental noise around 53 dB and limited vegetation cover within 500 m. These conditions describe an urban healthcare context with restricted vegetative cooling potential and increased sensitivity to overheating.

The simulation model is based on a representative standard patient room located in the middle of the ward (Fig. 3.3). The room is part of a linear sequence of inpatient rooms along a corridor and has approximate dimensions of 4.2 m by 6.5 m, including the bathroom. This room type is used as the reference geometry for the subsequent simulation scenarios.

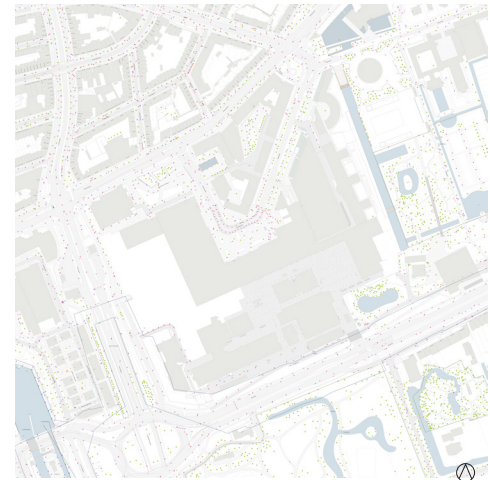


Fig. 3.1: 2D plan view of the current Erasmus MC situation. (Author's work)

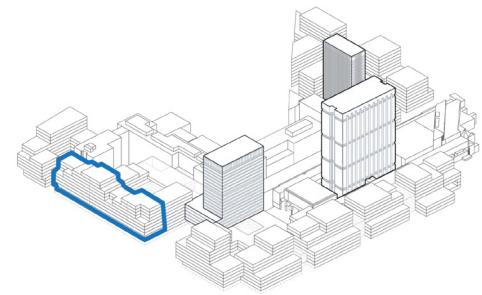


Fig. 3.2: 3D volume study of the Erasmus MC expansion, with the case-study wing marked in blue. Adapted from Erasmus MC (2026).



Fig. 3.3: Case-study floor plan of building level 6, with the representative patient room highlighted in blue. Adapted from Erasmus MC (2026).

3. CASE STUDY DESCRIPTION

3.2 User profiles

Healthcare buildings accommodate users with distinct physiological capacities, activity levels and exposure patterns. To support an occupant-centred assessment, three user profiles are defined for the case study: mobile patients, bedridden patients and staff. These profiles represent increasing levels of thermal vulnerability and decreasing adaptive capacity, as summarised in Fig. 3.4. Visitors are excluded from the analysis, as their health status and adaptive capacity are assumed to be closer to staff than to hospitalised patients.

Staff are treated as healthy adults with intact thermoregulation and relatively high *MET* values due to care-related activities. Mobile patients represent an intermediate group, retaining some behavioural adaptation while potentially experiencing reduced thermoregulatory capacity due to illness, fatigue, dehydration or medication. Bedridden patients form the most vulnerable group, because prolonged bed rest, limited movement and bedding insulation reduce heat dissipation. For this group, bedding and postures have been included in the *CLO* value.

Sleeping occupants and children under the age of ten are excluded because both require separate heat-balance assumptions. Sleep alters *MET* and thermoregulatory thresholds, while children differ from adults in body proportions, sweating capacity, vasomotor control, clothing dependence and exposure to local airflow (Almagro-Lidon et al., 2024; Zheng et al., 2024). Age and gender effects are acknowledged but treated as secondary to health condition, mobility, *CLO* and *MET*.

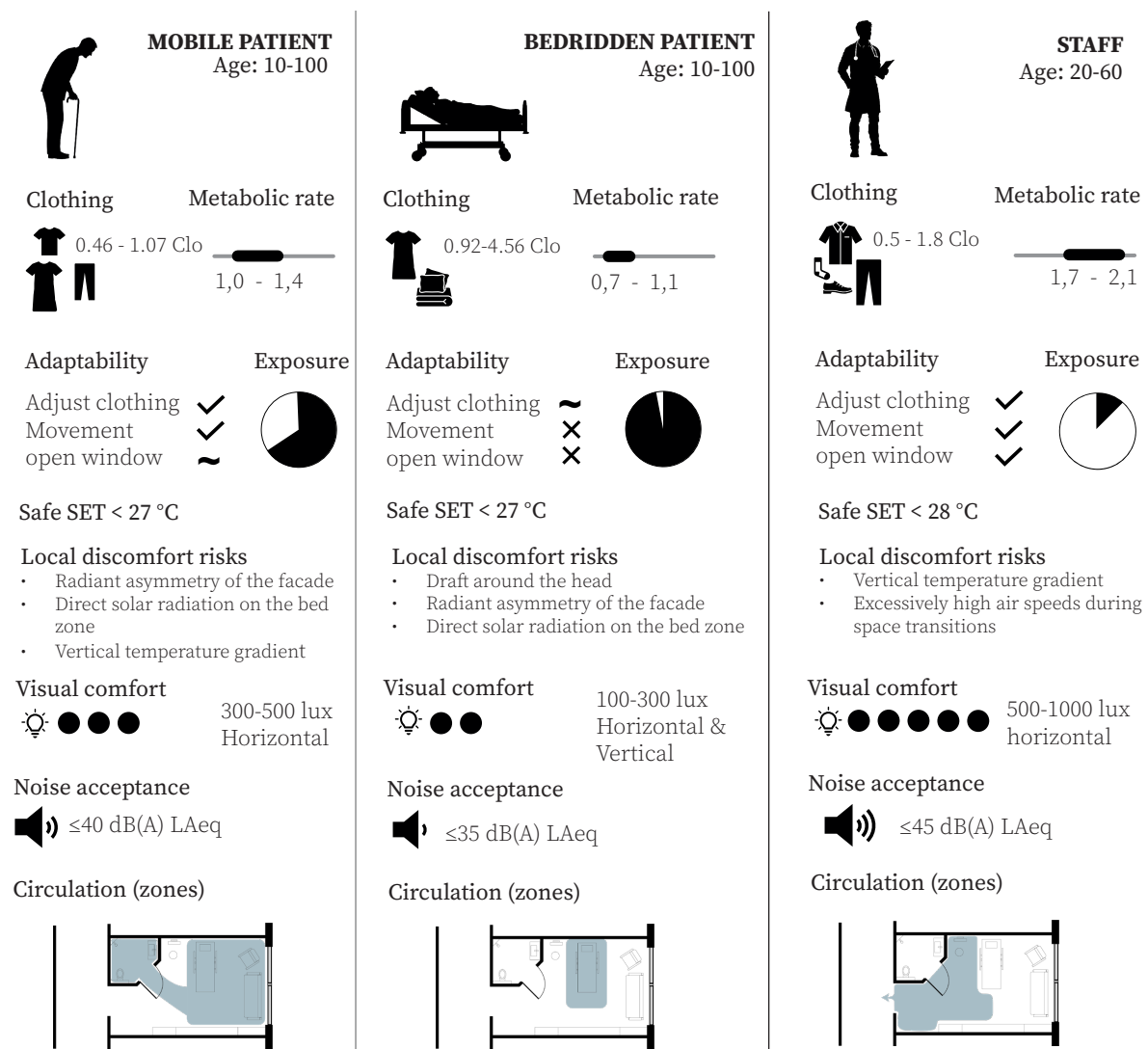


Fig. 3.4: Summary of user profiles. (Author's work)

3.3 Programme of requirements

The Erasmus Programme of Requirements for a regular patient room forms the baseline for the model, supplemented by literature-based criteria for evaluating occupant-level passive and hybrid cooling performance. Where the research applies stricter criteria than the PvE, such as SET limits, draught risk, local air velocity and solar exposure at bed level, these are treated as evaluation criteria rather than project requirements. This distinction is important because the original PvE primarily defines room performance at system and building level, whereas this research evaluates thermal comfort at occupant level for staff, mobile patients and bedridden patients. The complete programme of requirements for the simulation of the case study is shown in Table 3.1.

Category	Requirement / criterion	Value / target	Basis
Room type	Patient room type	Regular single-patient room	Erasmus MC PvE
Room function	Medical use classification	G1	Erasmus MC PvE
Floor area	Minimum room area	$\geq 23 \text{ m}^2$, excluding sanitary space	Erasmus MC PvE
Occupancy	Number of persons	3 persons	Erasmus MC PvE
Clear height	Minimum clear room height	3000 mm	Erasmus MC PvE
View	External visual connection	View of horizon or sky	Erasmus MC PvE
Privacy	Visual privacy and supervision	Privacy with possibility of visual supervision	Erasmus MC PvE
Transparency	Façade / room transparency	As transparent as possible, with rapid blinding option	Erasmus MC PvE
Daylight	Daylight access	Required	Erasmus MC PvE
General illuminance	General lighting level	300 lux	Erasmus MC PvE
Examination illuminance	Local examination lighting	1000 lux	Erasmus MC PvE
Glare	Glare rating	UGR 19	Erasmus MC PvE
Thermal comfort class	Comfort class	NEN-ISO 7730 class B	Erasmus MC PvE
Summer temperature	Indoor summer temperature	21–25 °C, class A	Erasmus MC PvE
Winter temperature	Indoor winter temperature	20–24 °C + individual control, class A	Erasmus MC PvE
Relative humidity	Indoor RH range	30–70%	Erasmus MC PvE
Ventilation rate	Air change rate	3 ACH	Erasmus MC PvE
Ventilation rate per person	Outdoor air supply	60 m ³ /h per person	Erasmus MC PvE
CO ₂ control	Demand-controlled ventilation	CO ₂ -dependent ventilation, +450 ppm	Erasmus MC PvE
Air filtration	Filter requirement	ISO ePM1 > 80%	Erasmus MC PvE
Ventilation control	Occupancy or demand-based detection	Required	Erasmus MC PvE
Pressure hierarchy	Room pressure	Negative pressure	Erasmus MC PvE
Leakage class	Air leakage class	L1, leakage factor 0.027000	Erasmus MC PvE
Equipment load	Internal equipment load	10 W/m ²	Erasmus MC PvE
Acoustic comfort	Building services sound pressure level	$\leq 30 \text{ dB}$	Erasmus MC PvE
External noise	Indoor sound pressure due to external noise	$\leq 40 \text{ dB LAeq}$	Erasmus MC PvE
Airborne sound insulation to corridor	$D_{nT,A}$ to circulation areas	$\geq 33 \text{ dB(A)}$	Erasmus MC PvE
Airborne sound insulation to occupied rooms	$D_{nT,A}$ to occupied rooms	$\geq 42 \text{ dB(A)}$	Erasmus MC PvE
Stratification	Vertical air temperature difference	$\leq 2 \text{ K/m}$	ISO 7730 / comfort literature
Radiant asymmetry	Warm ceiling / cool ceiling / warm wall / cool wall	$\leq 5 \text{ K} / \leq 14 \text{ K} / \leq 23 \text{ K} / \leq 10 \text{ K}$	ISO 7730 / ASHRAE comfort criteria
Physiological heat strain	SET threshold	SET $\leq 27 \text{ °C}$	Research criterion, based on conservative interpretation of heat-stress literature
Draught risk	Patient-zone draught risk	DR < 10%	ISO 7730 / patient vulnerability
Patient-zone air velocity	Bed-level airflow	Low, stable and spatially uniform	Literature review / patient vulnerability
Staff-zone air velocity	Staff circulation airflow	Higher summer air speeds acceptable	Literature review / elevated air speed comfort
Purge ventilation	Peak overheating ventilation capacity	Approx. 6 dm ³ /s/m ² floor area	Literature / ventilation guidance
Airflow path	Ventilation organisation	Façade inlet to high-level exhaust, avoiding short-circuiting	Literature review / passive ventilation principles
Solar control	External solar shading	Prioritised on sun-exposed façades	Literature review
Bed solar exposure	Direct solar radiation on patient bed	Avoided	Literature review / occupant-level radiant comfort
Hybrid cooling	Mechanical fallback	Passive and hybrid concept should reduce, not replace, active cooling	Research objective

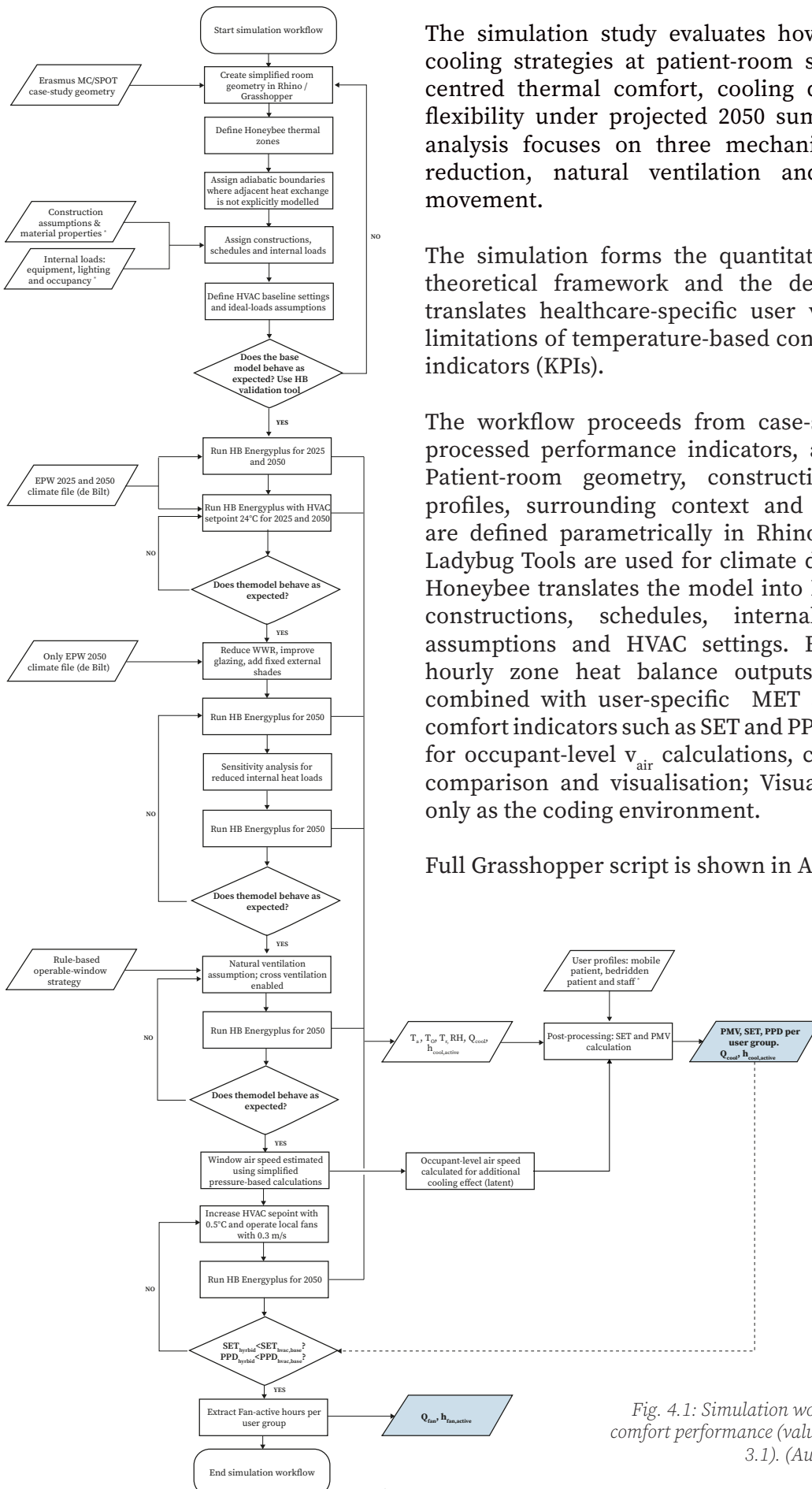
Table 3.1: Programme of Requirements for the case study simulation, partly based on the Erasmus MC Programme of Requirements, supplemented with literature-based criteria.

4

ENERGY AND THERMAL COMFORT PERFORMANCE

This chapter evaluates the thermal comfort and energy performance of the case study through simulation. It defines the model setup, climate data, scenarios, comfort indicators and energy-related KPIs, before presenting results for the free-floating case, HVAC baseline, passive envelope measures, natural ventilation, local air movement and hybrid cooling. The scenario comparison quantifies how passive and hybrid strategies affect occupant-centred comfort, cooling demand and cooling setpoint flexibility under projected 2050 climate conditions.

4.1 Simulation objective and methodology



The simulation study evaluates how passive and hybrid cooling strategies at patient-room scale affect occupant-centred thermal comfort, cooling demand and setpoint flexibility under projected 2050 summer conditions. The analysis focuses on three mechanisms: solar heat-gain reduction, natural ventilation and occupant-level air movement.

The simulation forms the quantitative link between the theoretical framework and the design implications. It translates healthcare-specific user vulnerability and the limitations of temperature-based control into performance indicators (KPIs).

The workflow proceeds from case-study inputs to post-processed performance indicators, as shown in Fig. 4.1. Patient-room geometry, construction properties, user profiles, surrounding context and future weather data are defined parametrically in Rhino 8 and Grasshopper. Ladybug Tools are used for climate data processing, while Honeybee translates the model into EnergyPlus, including constructions, schedules, internal loads, ventilation assumptions and HVAC settings. EnergyPlus calculates hourly zone heat balance outputs. These outputs are combined with user-specific MET and CLO to calculate comfort indicators such as SET and PPD. Python is then used for occupant-level v_{air} calculations, control logic, scenario comparison and visualisation; Visual Studio Code serves only as the coding environment.

Full Grasshopper script is shown in Appendix K.

Fig. 4.1: Simulation workflow energy and thermal comfort performance (values for * can be found in Table 3.1). (Author's work)

Model Simplifications and Input Parameters

The simulations use fixed input values for user profiles, occupancy, room geometry, constructions, internal loads and building-physics assumptions, as defined in Section 3.3 and Appendix G. Occupancy schedules are provided in Appendix H. These inputs remain constant across all scenarios to isolate the effect of the selected design and control variables: WWR, glazing composition, façade U-value, HVAC setpoints, fixed external shading and operable window control. These variables are linked to the scenario structure in following sections. Thermal comfort is assessed using the user profiles defined in Section 3.2. MET and CLO values are kept constant within each profile, and the corresponding input values and sensor locations are summarised in Table 4.1.

Bedridden patient			Parameter	Input value
CLO (R_i)	1.43	Bedridden + awake + underwear + short pajamas + 48% coverage bed sheet	Patient room dimensions	4.2 m × 6.5 m
MET	1.057	Age: 45, Weight: 72kg, Height: 1.70m PAL: 1.2	Building level	Level 6, approximately +20 m
Posture	Supine		Floor area	27.3 m ²
SHARP	90	Sunlight on side of face	Orientation	South-west
Sensor point	(B)	Bed position	Occupancy density	0.25 persons/m ²
Mobile patient			Lighting load	3.8 W/m ²
CLO	0.46	Sitting + awake + underwear + short pajamas + none coverage	Equipment load	10.0 W/m ²
MET	1.23	Age: 45, Weight: 72kg, Height: 1.70m PAL:1.4	Infiltration rate	0.0003 m ³ /s/m ³
Posture	Seated		Construction type	Mass
SHARP	180	Sunlight on back of the body	Exterior wall build-up	Stucco – concrete – insulation – gypsum
Sensor point	(A)	Window position	Interior wall build-up	Gypsum board – air gap – gypsum board
Staff			Weather data	EPW 2050, Heiranipour
CLO	0.64	undewear + headgear + Coat + Trousers + Socks + clogs + gloves		
MET	1.8	Age: 45, Weight: 72kg, Height: 1.70m PAL:1.8		
Posture	Standing			
SHARP	90	Sunlight on side of face		
Sensor point	(C)	Staff zone		

Table 4.1: Fixed inputs for the performance simulation of the case study.

The model was intentionally simplified to remain feasible within the scope of this thesis; a detailed overview of simplifications and assumptions is provided in Appendix J. The analysis focuses on one representative patient room where adjacent spaces are included only where thermally relevant, while remaining boundaries are treated as adiabatic. Sanitary spaces, detailed furniture, medical equipment geometry and open-door airflow are excluded.

The model uses simplified construction assumptions, deterministic occupancy schedules and well-mixed thermal zones, consistent with the EnergyPlus single-node zone air model. Natural ventilation and local air-speed effects are represented through simplified airflow assumptions (Appendix M) and post-processed comfort calculations. HVAC operation is modelled with ideal loads and fixed setpoints, excluding system dynamics, part-load behaviour and control delays. Consequently, the results should be interpreted as comparative scenario outcomes rather than exact predictions of real patient-room performance.

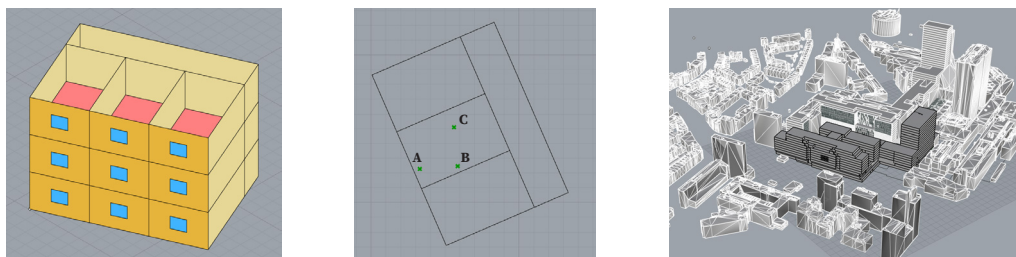


Fig. 4.2: Simulation model overview: (a) isometric view of the southwest Honeybee model with adiabatic boundary surfaces; (b) wireframe plan with sensor points at the window location, bed position and staff zone; (c) simulation context.

4. ENERGY AND THERMAL COMFORT PERFORMANCE

Key performance indicators (KPIs)

The simulation results are evaluated using a set of key performance indicators that link occupant-centred thermal comfort to passive design performance and residual cooling demand. These KPIs allow the scenarios to be compared consistently across user groups, climate files and cooling strategies.

KPI 1: Average SET per user group

Measures the average perceived thermal condition for each user group over the analysed summer period. Where u represents the user group: mobile patient, bedridden patient or staff.

$$\overline{SET}_u = \frac{1}{N} \sum_{t=1}^N SET_{u,t} \quad \text{Eq. 28}$$

KPI 2: SET exceedance hours

Counts the number of hours in which the selected SET threshold is exceeded. This is the main overheating-risk indicator.

$$H_{SET>lim,u} = \sum_{t=1}^N I(SET_{u,t} > SET_{lim}) \cdot \Delta t \quad \text{Eq. 29}$$

KPI 3: Average T_o

Describes the room-level thermal condition and is mainly used to compare passive envelope variants and internal load reductions.

$$\overline{T}_{op} = \frac{1}{N} \sum_{t=1}^N T_{op,t} \quad \text{Eq. 30}$$

KPI 4: Natural ventilation availability

Quantifies whether natural ventilation is available as a driving force. It captures wind-direction dependency and intermittency.

$$H_{v=0} = \sum_{t=1}^N I(v_{win,t} = 0) \cdot \Delta t \quad \text{Eq. 31}$$

$\overline{v}_{win}, \quad v_{win,max}$

KPI 5: Occupant-level air-speed effect

Measures how much local air movement reduces perceived heat stress beyond the effect of lowering T_o .

$$\Delta SET_{v,u,t} = SET_{sensible,u,t} - SET_{sensible+airspeed,u,t}$$

$$\overline{\Delta SET}_{v,u}, \quad \Delta SET_{v,u,max} \quad \text{Eq. 32}$$

KPI 6: Hybrid setpoint flexibility

Determines how far the cooling setpoint can be raised while maintaining equal or improved comfort compared with the HVAC baseline.

$$\Delta T_{set} = T_{set,hybrid} - T_{set,baseline} \quad \text{Eq. 33}$$

$$SET_{hybrid,u} \leq SET_{baseline,u}$$

KPI 7: Active cooling hours

Counts the number of hours during which active cooling is required.

$$H_{cool,active} = \sum_{t=1}^N I(Q_{cool,t} > 0) \cdot \Delta t \quad \text{Eq. 34}$$

KPI 8: Fan operation hours

Estimates how many hours local fans would operate under the assumed PMV-based control strategy. This KPI is needed for fan electricity calculations and for assessing practical feasibility.

$$H_{fan,u} = \sum_{t=1}^N I(PMV_{u,t} > 0.5) \cdot \Delta t \quad \text{Eq. 35}$$

KPI 9: Q_{cool} reduction

Quantifies the reduction in thermal cooling load. In the ideal-loads model this represents the heat that must be removed, not final electricity use.

$$\Delta Q_{cool} = \frac{Q_{cool,baseline} - Q_{cool,hybrid}}{Q_{cool,baseline}} \cdot 100 \quad \text{Eq. 36}$$

4. ENERGY AND THERMAL COMFORT PERFORMANCE

Simulation scenarios

The drawings in this section are simplified abstractions of the patient room, used solely to illustrate scenario concepts and variable changes. For clarity, the room is shown in isolation and should not be interpreted as a full representation of the case study. In each scenario, parameters changed relative to the reference case are indicated in bold.

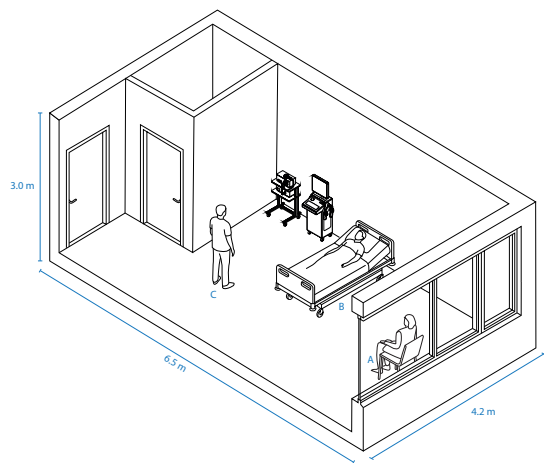


Fig. 4.3a: Free-floating scenario without active or passive cooling measures. Position A represents mobile patients, B bedridden patients and C staff. (Author's work)

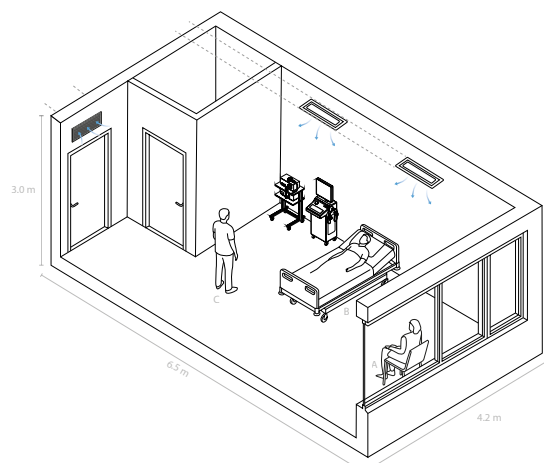


Fig. 4.3b: Baseline patient-room configuration with ceiling-based HVAC supply and corridor-side extract airflow. (Author's work)

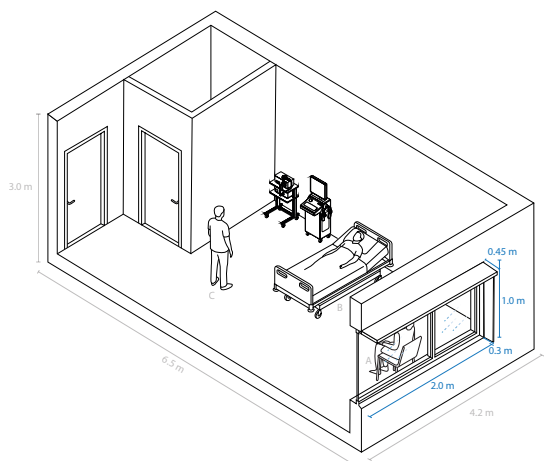


Fig. 4.3c: Passive envelope scenario with reduced WWR, fixed vertical and horizontal external shading, and solar-control glazing. (Author's work)

1. Free-floating (intrinsic thermal exposure baseline)

A basic shoebox model without active systems or passive design measures is used as a reference. This scenario illustrates indoor thermal conditions under future climate in NL and provides insight into heat accumulation.

WWR:	0.34
Window: g-value	0.4
U-value	1.20 W/m ² -k
Exterior window:	HR++
HVAC:	None
Shades:	None

2. HVAC baseline

The same geometry is maintained, but thermal comfort is ensured through a conventional HVAC system. No passive interventions are included. This scenario reflects current design practice and serves as the main benchmark for comparison.

WWR:	0.34
Window: g-value	0.4
U-value	1.20 W/m ² -k
Exterior window:	HR++
HVAC:	Summer setpoint 24°C
Shades:	None
Openable windows	none

3. Passive envelope

Reducing the solar heat gain by reducing WWR, installing fixed external shades and upgraded glazing while considering consistent visual comfort. The calculated WWR and shading depths are provided in Appendix L.

WWR:	0.16
Window: g-value	0.3
U-value	1.00 W/m²-k
Exterior window:	Solar G
HVAC:	None
Shades:	Horizontal + vertical
Openable windows	none

4. ENERGY AND THERMAL COMFORT PERFORMANCE

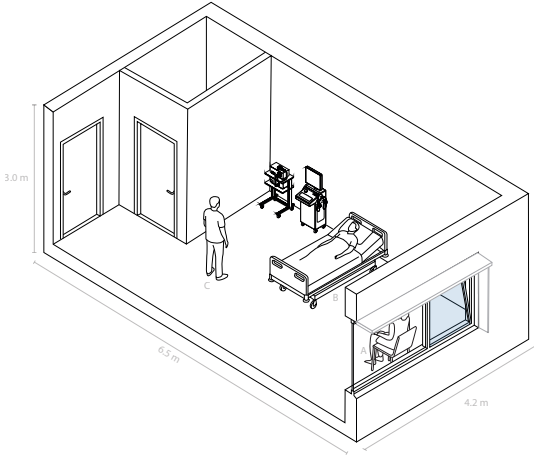


Fig. 4.4a: Natural ventilation scenario with openable windows and an opening factor of 0.2, including sensible and latent heat removal. (Author's work)

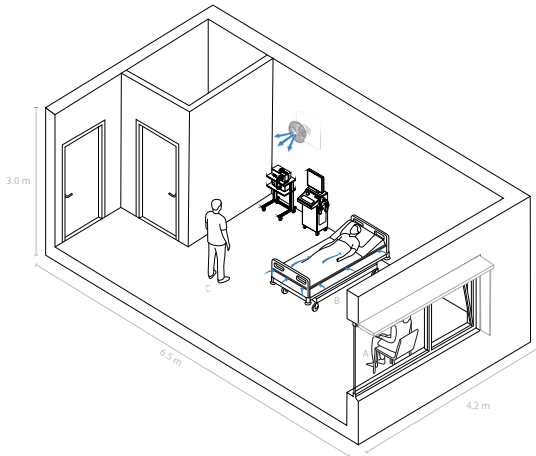


Fig. 4.4b: Local fan scenario with additional airflow for staff and a bed-integrated fan for the bedridden patient. (Author's work)

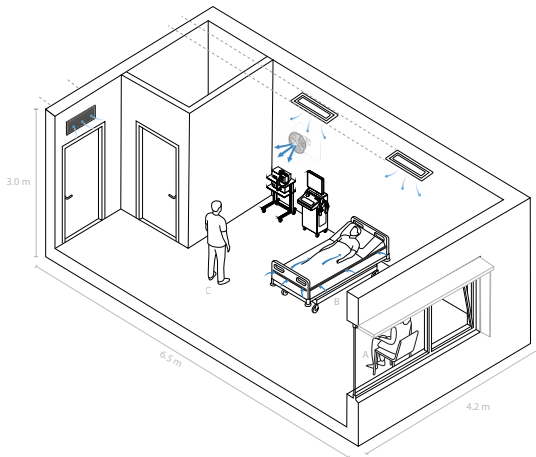


Fig. 4.4c: Hybrid scenario combining all passive measures, local fans and HVAC operation with higher temperature setpoints. (Author's work)

4. Natural ventilation

Operable windows are assessed as a natural ventilation strategy for heat dissipation. Behavioural schedules are used to control window opening, and both sensible heat removal and air-speed-related comfort effects are analysed. The estimation of v_{air} is explained in Appendix M.

WWR:	0.16
Window: g-value	0.3
U-value	1.00 W/m ² -k
Exterior window:	Solar G
HVAC:	None
Shades:	Horizontal + vertical
Opening fraction:	0.2
Opening rules:	

$$W(t) = \begin{cases} 1, & \text{if } T_{in}(t) > 25^{\circ}\text{C} \wedge T_{out}(t) > 18^{\circ}\text{C} \wedge T_{out}(t) < 27^{\circ}\text{C} \wedge \Delta T(t) < 2^{\circ}\text{C} \\ 0, & \text{otherwise} \end{cases}$$

5. Additional local fans

Local fans are used as a demand-based strategy to provide controlled occupant-level air movement when PMV exceeds 0.7.

WWR:	0.16
Window: g-value	0.3
U-value	1.00 W/m ² -k
Exterior window:	Solar G
HVAC:	None
Shades:	Horizontal + vertical
Fan operation:	

$$F_u(t) = \begin{cases} 1, & \text{if } PMV_u(t) > 0.7 \\ 0, & \text{if } PMV_u(t) \leq 0.7 \end{cases}$$

6. Hybrid operation

HVAC with custom setpoints is added to remove residual heat. This is where all scenarios come together to analyse setpoint flexibility.

WWR:	0.16
Window: g-value	0.3
U-value	1.00 W/m ² -k
Exterior window:	Solar G
HVAC:	Min $E_{HVAC, new}$ $SET_{new} - SET_{base}$ $< \epsilon_{SET}$
Shades:	Horizontal + vertical
Fan operation:	

$$F_u(t) = \begin{cases} 1, & \text{if } PMV_u(t) > 0.7 \\ 0, & \text{if } PMV_u(t) \leq 0.7 \end{cases}$$

4.2 Simulation results

4.2.1 HVAC baseline performance under current and future climate conditions

The dry-bulb temperature profiles in Fig. 4.5 show that the 2050 weather file is generally warmer than the 2025 file, although the difference varies throughout the summer period. The 2050 dataset retains the hourly fluctuation pattern of the reference climate file, but shifts the temperature level upwards according to the future climate scenario. This is also reflected in the daytime averages: the dry-bulb temperature increases from 19.6°C to 22.4°C, the global horizontal radiation increases from 412.0 Wh/m² to 439.6 Wh/m², and the wind speed decreases from 4.3 m/s to 3.7 m/s (Appendix N.1). As a result, warm episodes become more frequent and persistent, with several peaks exceeding 30°C.

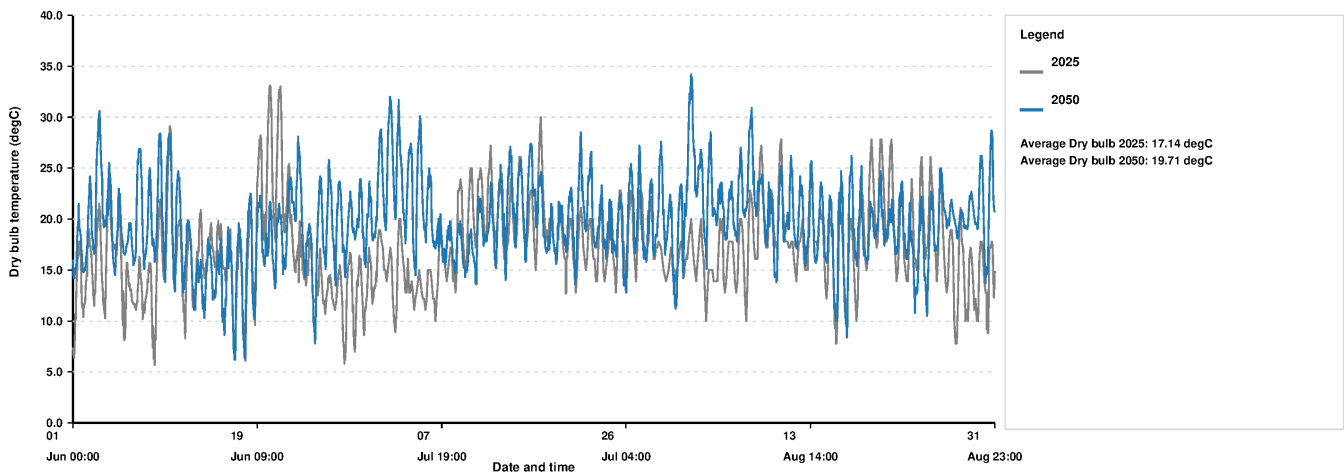


Fig. 4.5: Hourly dry-bulb temperature from 1 June to 31 August for 2025 and 2050 weather scenarios.

The two SET graphs in Fig. 4.6 and 4.7 compare the three user groups for the year 2025 and 2050. In the HVAC baseline scenario using 2025 weather data in Fig. 4.6, the mobile patients show an average SET of 22.6°C and no exceedance hours above 27°C. Although this remains below the selected threshold, it indicates relatively cool summer conditions for this group, which is reflected in the fact that the PPD exceeds 10% during 77% of the time (Appendix N.2). For bedridden patients, the average SET is 27.9°C, with 1763 exceedance hours. For staff, the average SET is 27.2°C, with 1401 exceedance hours. In both latter cases, discomfort is primarily associated with slightly warm conditions, with PPD values above 10% during 29.4% and 25.3% of the time respectively (Appendix N.2).

When the same baseline is evaluated using morphing-based 2050 weather data in Fig. 4.7, the average SET increases by 2.57°C for mobile patients, 1.81°C for bedridden patients, and 2.96°C for staff compared to 2025. This is accompanied by a 23.9% increase in exceedance hours for bedridden patients and a 57.0% increase for staff. For mobile patients, exceedance above 27°C remains absent and the share of hours with PPD above 10% decreases to 4.2%. This can largely be explained by the relatively low CLO of this group, which causes the same indoor environment to be perceived as cooler than by bedridden patients and staff.

SET follows the general outdoor temperature profile, but is moderated by the HVAC baseline assumptions. Weather-driven peaks produce short-term increases in SET, while cooler periods reduce thermal exposure. The response differs by user group: mobile patients remain below the 27°C threshold, whereas bedridden patients and staff remain close to or above this threshold during substantial parts of the summer.

1 August and 3 June, shown in Fig. 4.8, indicate that increases in T_o and SET are most pronounced at night and in the late afternoon. This is consistent with projected future climate conditions and literature, showing reduced day-night temperature differences and increased solar intensity. The late-afternoon peak is especially relevant for the southwest façade, where low-angle solar radiation may increase heat gains and occupant-level radiant exposure.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

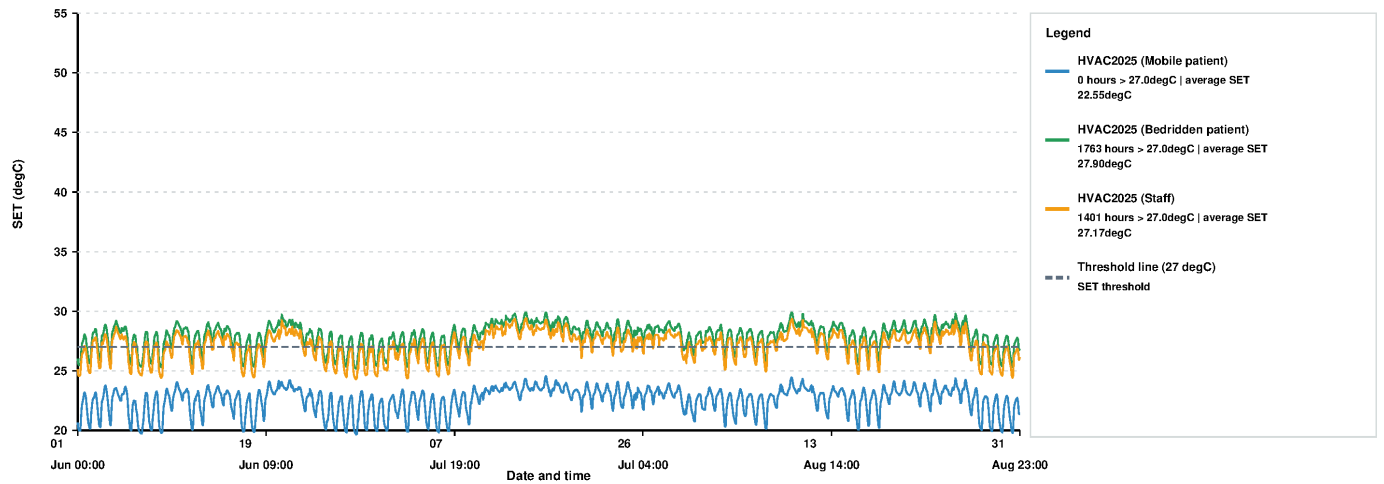


Fig. 4.6: Hourly SET from 1 June to 31 August for the HVAC baseline scenario using the 2025 EPW weather file, shown for mobile patients, bedridden patients and staff.

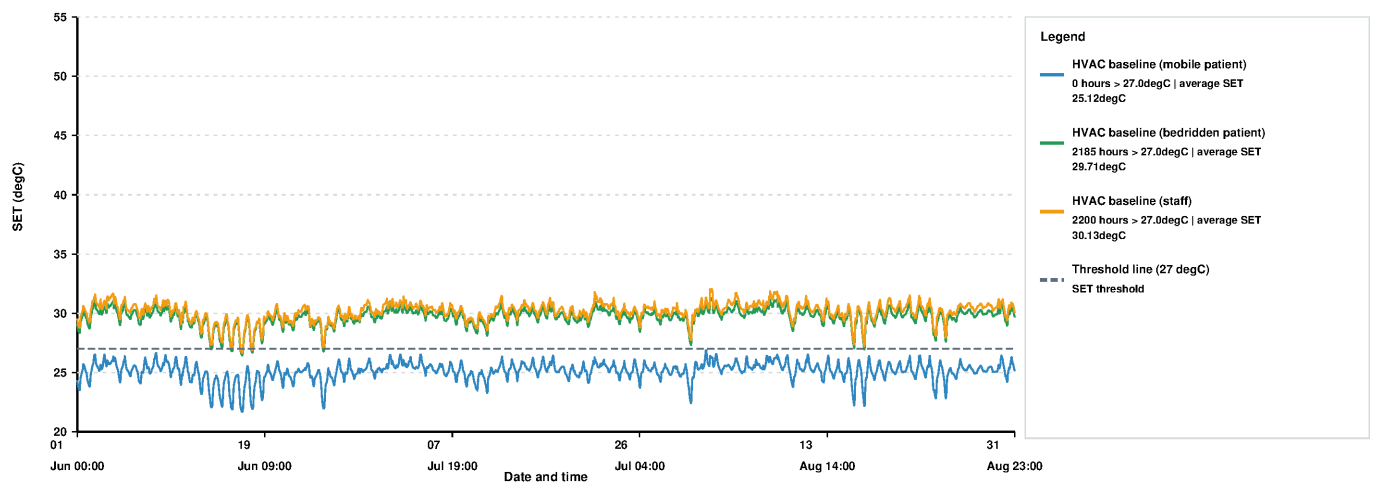


Fig. 4.7: Hourly SET from 1 June to 31 August for the HVAC baseline scenario using the 2050 EPW weather file, shown for mobile patients, bedridden patients and staff.

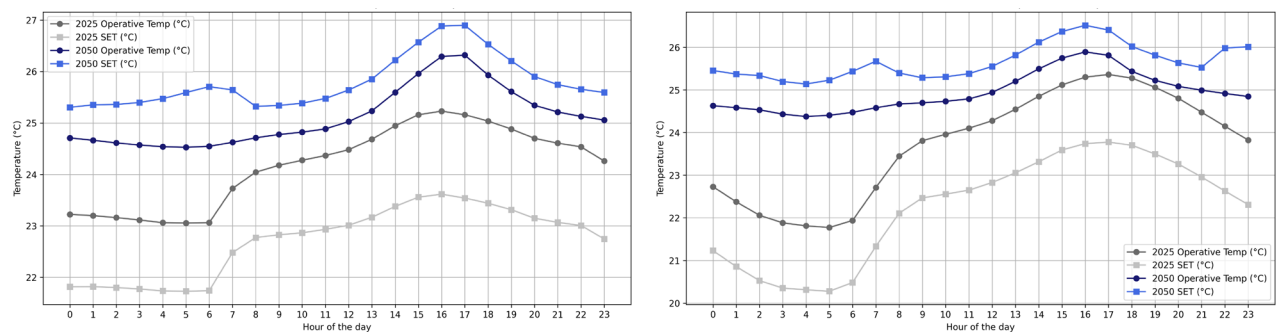


Fig. 4.8: Hourly SET and (T_o) for the HVAC baseline mobile-patient profile on 1 August (left) and 3 June (right), shown for the 2025 and 2050 weather scenarios. Critical hours provided in Appendix I.

4.2.2 Effect of a passive envelope and dominance internal heat gains

Although the passive envelope substantially reduces transmitted solar gains, its effect on thermal comfort remains limited as shown in Fig. 4.9. In the free-floating scenario, internal gains from lighting and medical equipment total approximately 13.7 kWh/m², making them larger than the transmitted solar gains and therefore a dominant contributor to the room heat balance. Even after an approximately 80% reduction in transmitted solar radiation in the passive envelope scenario (Appendix N), the hourly SET profile shows only minor improvement (Fig. 4.9). This indicates that internal heat gains become the dominant thermal load under continuous occupancy.

Fig. 4.9 shows that T_o remains well above the outdoor dry-bulb temperature for most of the summer period. The indoor thermal state is therefore not governed by outdoor temperature alone, but also by accumulated internal heat and thermal storage. SET exceeds T_o , reflecting the combined effect of elevated indoor temperatures, limited heat dissipation and user-specific parameters. Without active cooling or effective passive heat removal, heat accumulates over time, reinforced by 24/7 occupancy and the delayed release of heat stored in the concrete structure.

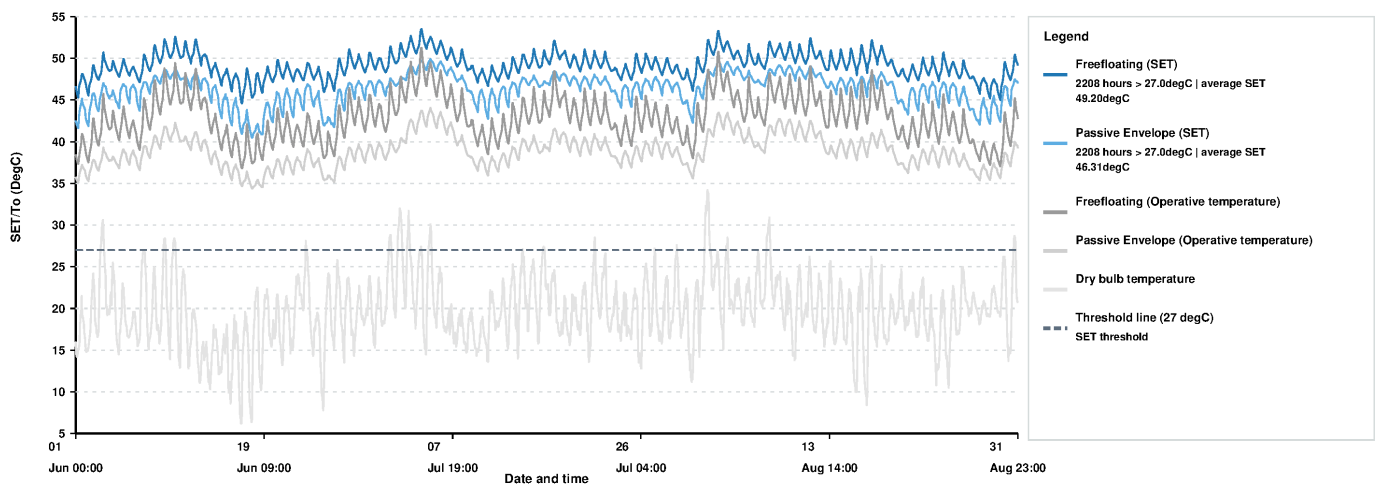


Fig. 4.9: Hourly SET over summer period for the freefloating and passive envelope scenario using EPW data file 2050, showing mobile patients.

The passive envelope alone therefore has limited capacity to improve thermal comfort under high internal gains and continuous occupation. This result should be interpreted as a stand-alone measure in a simplified free-floating setup. Since no active cooling, night ventilation or adaptive heat removal is included, the scenario primarily reveals the relative importance of internal and solar gains. In combination with ventilation or adaptive HVAC control, the reduction in solar gains may still provide a larger comfort benefit.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

Sensitivity to internal heat gains

To isolate the influence of internal heat gains, Fig. 4.10 compares adjusted heat-load assumptions within the passive-envelope scenario. This sensitivity test is used only to understand the relative effect of internal gains; all subsequent scenarios use the original internal load assumptions as proposed in the programme of requirements (Table 3.1). Each line represents one modified parameter: reduced equipment load, reduced occupancy or lightweight timber construction. Lighting was also tested, but its effect was too small to include meaningfully.

Reducing equipment load has the strongest effect on T_o . A 50% reduction in equipment use lowers the average T_o from 38.88°C to 35.59°C and the maximum T_o from 44.05°C to 40.01°C, while the timber construction and fewer people remain close to the reference case, with an average T_o of 38.21°C and 38.62°C. This indicates that equipment-related heat gains dominate the internal heat balance in this setup.

The temporal pattern remains similar across all variants, indicating that external climate conditions determine the timing of heat build-up, while internal gains mainly shift the temperature level. The equipment-reduction case remains consistently lower throughout summer, suggesting a structural reduction in heat accumulation. The timber construction shows slightly higher peak temperatures, likely due to lower thermal storage and reduced damping. Overall, the analysis confirms that internal heat-load management, particularly from medical and electrical equipment, is a critical precondition for effective passive cooling in continuously occupied patient rooms.

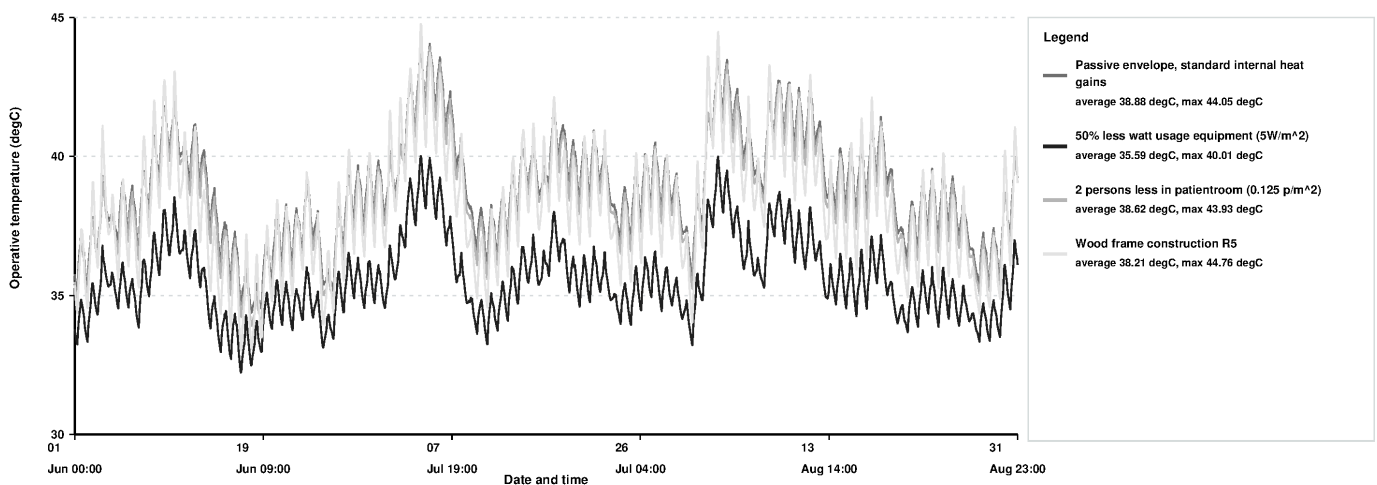


Fig. 4.10: Hourly T_o over the summer period for the passive-envelope scenario with reduced internal heat gains.

4.2.3 Effect of natural ventilation on occupant thermal comfort

Natural ventilation potential

The wind-speed graphs in Fig. 4.11 and Fig. 4.12 show that the potential for natural ventilation is highly intermittent. While the weather station records wind during most hours of the analysed summer period, the calculated v_{air} at the window is frequently zero. In total, 845 hours, corresponding to 38.3% of the analysed period, show no effective v_{air} at the window of the south-west facade patient room. This indicates that the availability of natural ventilation is not determined by outdoor v_{air} alone, but strongly depends on whether the wind direction creates a useful Δp across the façade opening.

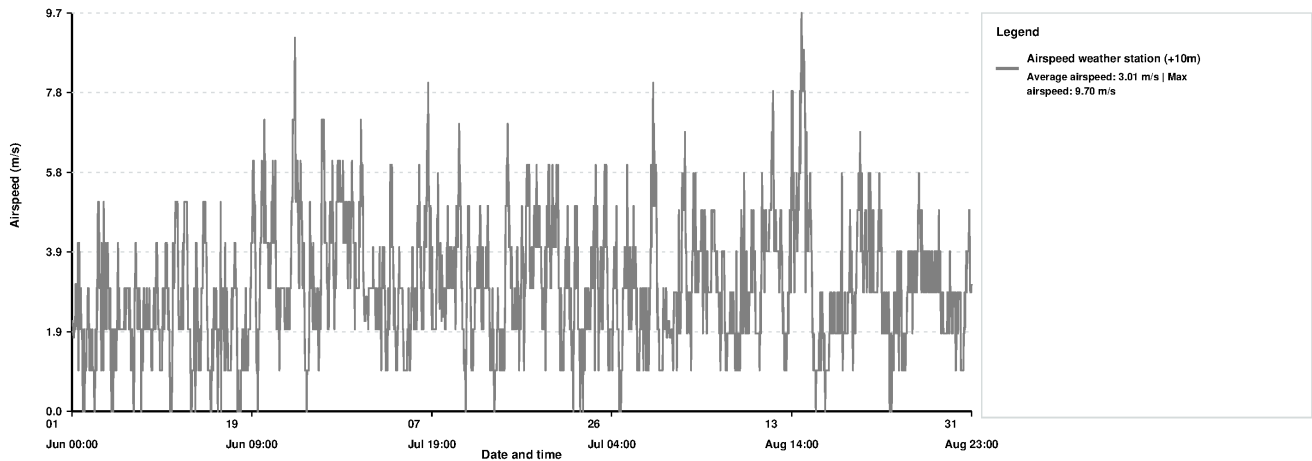


Fig. 4.11: Outdoor v_{air} at measuring location in De Bilt over the summer period

The time-series of $v_{air,window}$ in Fig. 4.12 further shows that ventilation potential occurs mainly in short, irregular episodes rather than as a continuous driving force. The average calculated $v_{air,window}$ is 0.64 m/s, while the maximum reaches 3.80 m/s. This suggests that openable windows can provide significant airflow during favourable wind conditions, but cannot be relied upon as a stable ventilation mechanism throughout the full summer period.

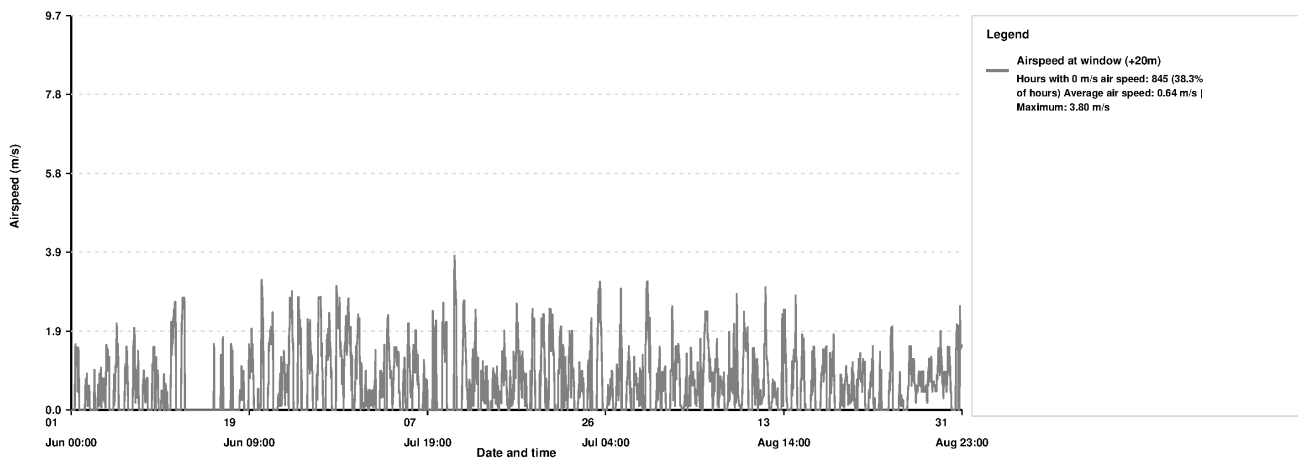


Fig. 4.12: Hourly $v_{air,window}$ over the summer period

The selected extreme days in Fig. 4.13 illustrate this variability. On the lowest average-wind day, calculated $v_{air,window}$ remains zero, indicating no wind-driven ventilation potential. The highest peak-wind day shows a short afternoon increase, whereas the highest average-wind day provides more sustained airflow throughout the day. This distinction is relevant for the subsequent analysis, as sensible and latent heat removal through open windows depends not only on the magnitude of $v_{air,window}$, but also on its timing and duration.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

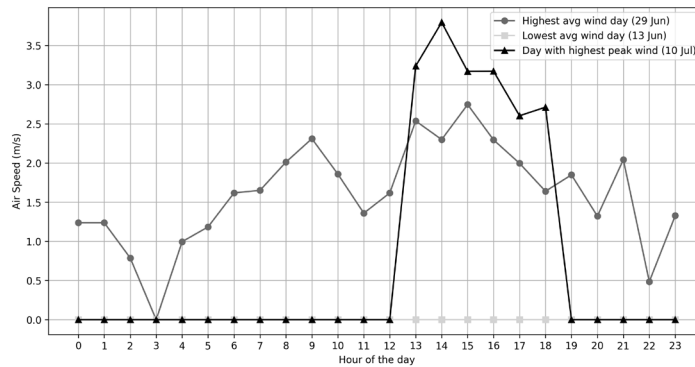


Fig. 4.13: Hourly wind speed for three critical days within the summer period.

Sensible versus latent heat removal

The v_{air} values for the various occupant locations have been calculated using the calculation in Appendix M, and the results for the various users are shown in Appendix N.5. The effect of natural ventilation on SET was assessed in two steps and explained here for the mobile patient because they are located closest to the window and experience the most natural airflow. The results for the other users can be found in Appendix N.8 and N.10. First, only sensible heat removal was included by reducing the T_o through window-driven ventilation (Fig. 4.14). In this case, the average SET decreases to 30.99°C, but 1981 hours still exceed the 27°C threshold. This shows that sensible cooling alone reduces part of the thermal load, yet it is insufficient to maintain acceptable thermal comfort during most of the summer period.

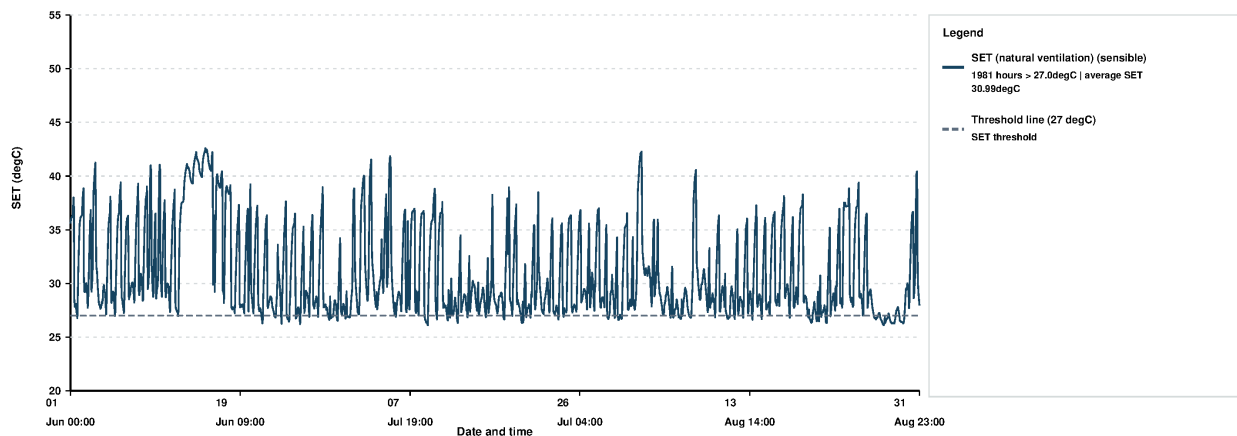


Fig. 4.14: Hourly SET for mobile patients over the summer period, including sensible heat removal through ventilation.

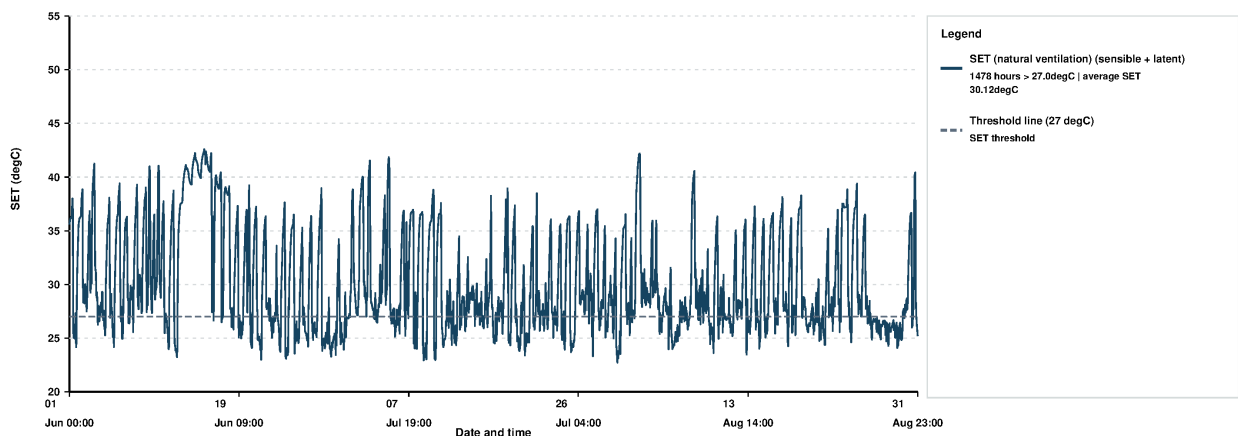


Fig. 4.15: Hourly SET for mobile patients over the summer period, including sensible and latent heat removal through ventilation.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

In the second step, the calculated v_{air} at the window was translated to the patient location according to the estimation described in Appendix M. This local v_{air} was then included as an additional input parameter in the SET calculation. Compared with the sensible-only case, Fig. 4.15 shows that the average SET decreases further to 30.12°C and the number of exceedance hours is reduced to 1478. The improvement therefore results not only from lower T_o , but also from increased convective and evaporative heat loss at human body level.

The hourly SET difference between both calculations in Fig. 4.16 shows that this additional air-speed effect is highly variable. The average reduction is 0.87°C, but during favourable wind conditions the difference reaches up to approximately 4.5°C. At many hours, however, the difference is close to zero, which corresponds to periods with little or no effective airflow at the window. This confirms that the comfort benefit of openable windows is intermittent: natural ventilation can substantially reduce perceived heat stress during wind-driven periods, but its performance depends strongly on the timing and magnitude of available airflow.

Overall, the results indicate that latent and convective heat removal at occupant level are relevant for the perceived thermal comfort of mobile patients. Nevertheless, natural ventilation alone does not bring the SET consistently below the comfort threshold. Its main value lies in reducing peak discomfort and shortening the duration of exceedance hours, rather than providing a stable replacement for active cooling.

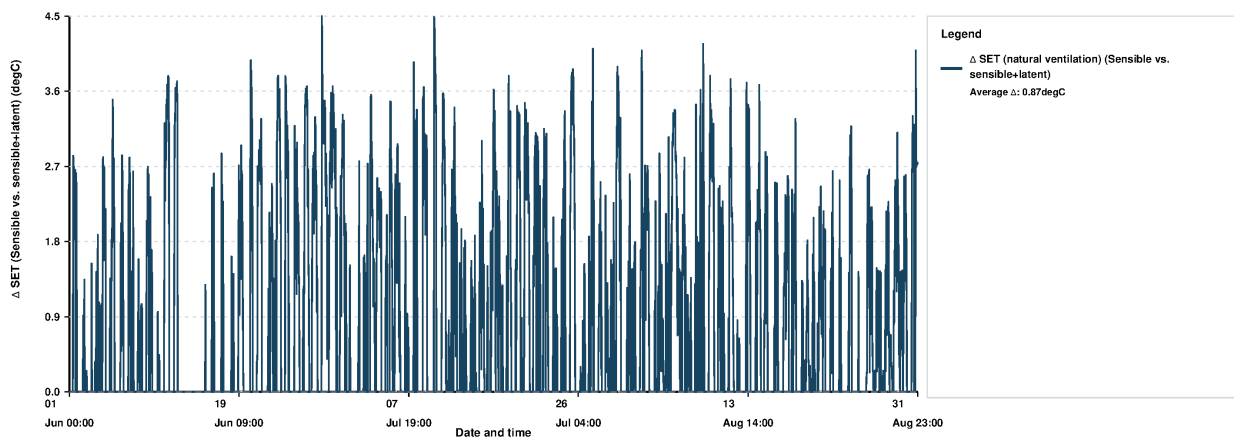


Fig. 4.16: Delta SET between sensible heat removal and sensible + latent heat removal over the summer period for scenario natural ventilation.

The dot plots in Fig. 4.17-4.19 clarify how local v_{air} affects SET . Each point represents one hourly condition, with darker markers indicating higher v_{air} at the occupant position. Across all user groups, SET generally increases with T_o , confirming that T_o remains the dominant driver of thermal exposure. However, at comparable T_o , higher v_{air} consistently correspond to lower SET values, indicating that air movement reduces perceived thermal load without necessarily lowering room temperature.

This effect is most pronounced for mobile patients. Several hours with T_o around 27–30°C shift towards or below the 27°C SET threshold under higher local v_{air} , consistent with lower CLO and greater convective and evaporative heat-loss potential. For bedridden patients and staff, the same mechanism is visible but less sufficient to remain below the threshold. This is related to higher insulation and limited exposure for bedridden patients, and higher metabolic heat production for staff. Differences in room position further affect the local v_{air} experienced by each group.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

The relatively flat upper boundary of the point cloud represents hours with little or no air movement. Under these conditions, SET is mainly governed by T_o , and fixed occupant parameters, while sensitivity to small v_{air} variations is limited. The darker points below this boundary therefore indicate hours in which natural ventilation provides an occupant-level cooling effect.

Overall, the results show that natural ventilation primarily modifies occupant heat exchange rather than directly reducing room temperature. The same T_o can therefore result in different SET values depending on local v_{air} , occupant position, CLO and MET .

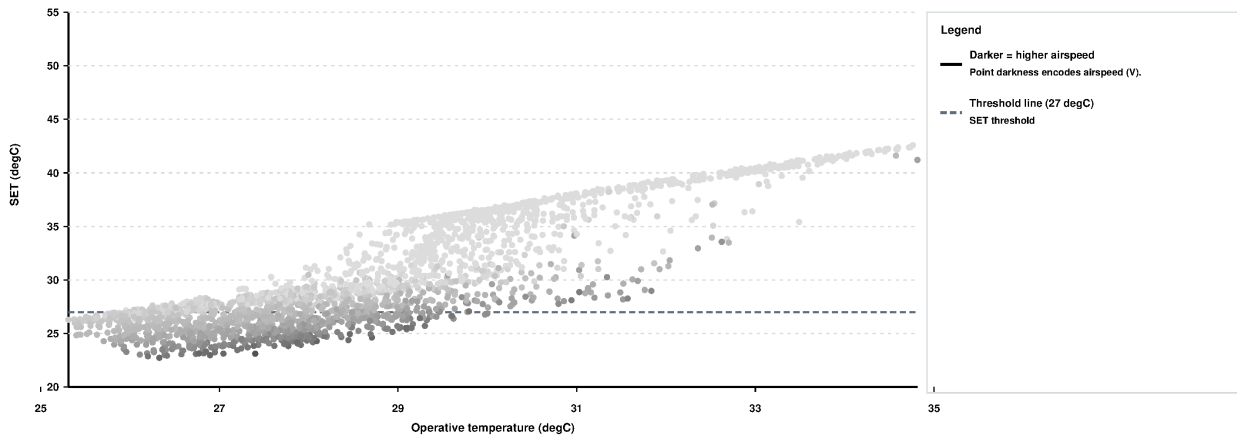


Fig. 4.17: hourly SET and T_o for mobile patient during the summer period.

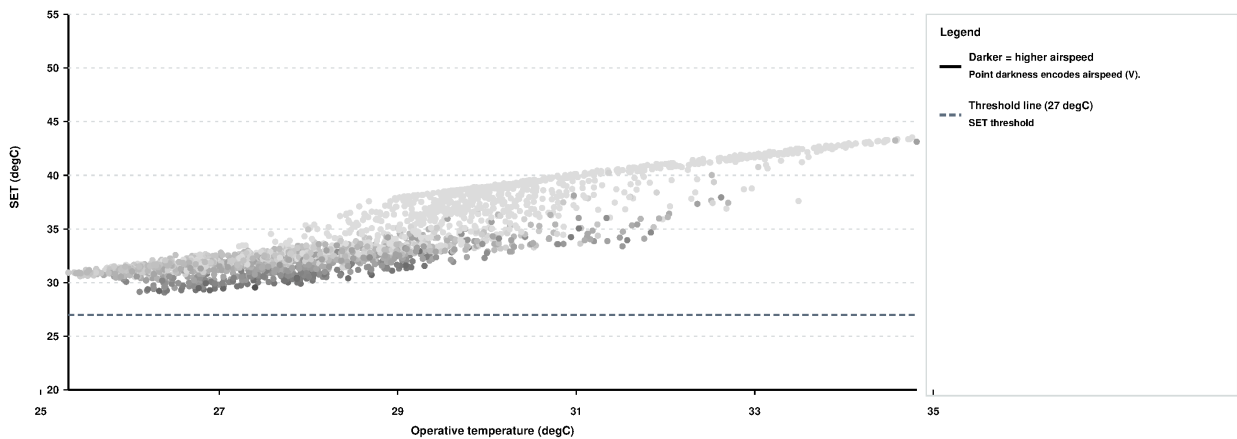


Fig. 4.18: hourly SET and T_o for bedridden patient during the summer period.

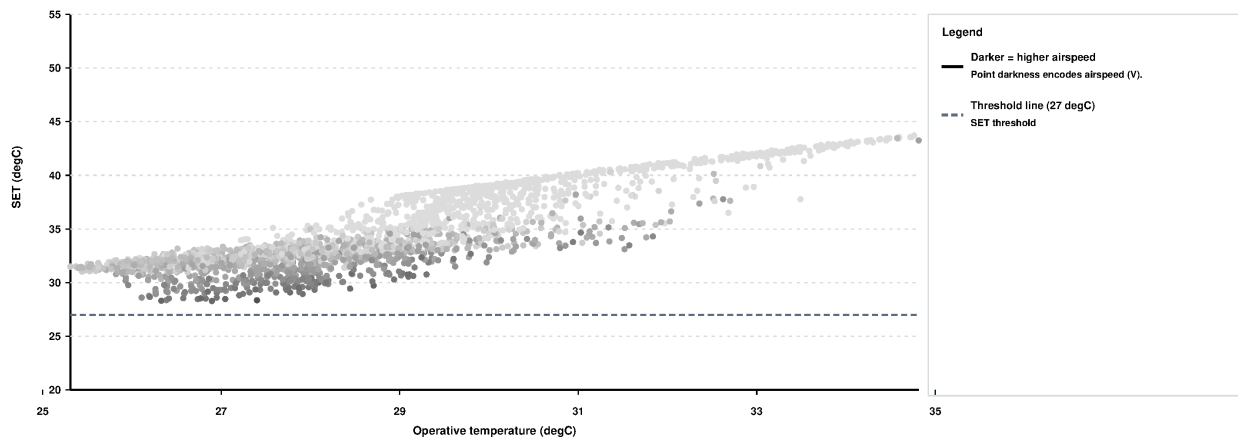


Fig. 4.19: hourly SET and T_o for staff during the summer period.

4.2.4 Hybrid operation: effect of fan operation on occupant thermal comfort

The PMV values in Fig. 4.20–4.22 represent the hybrid scenario after implementation of the preceding passive and natural ventilation measures, with the HVAC cooling setpoint increased to 26°C. Local fan activation is introduced as a final comfort correction to approach the comfort performance of the HVAC baseline. The fans are modelled as 15 W on/off devices, without variable speed control. When active, they provide a local air speed of 0.4 m/s, selected as a balance between perceptible comfort improvement and clinical constraints related to draught, hygiene and acceptability. A PMV threshold of 0.7 was selected instead of 0.5 to represent a more realistic control assumption, as occupants are unlikely to activate a fan immediately under slightly warm conditions.

The results show a clear user-dependent activation pattern. For mobile patients, the fan is not activated during most of the analysed summer period, as there are only 22 hours with $PMV > 0.7$. This indicates that residual discomfort is limited for this profile and does not justify continuous local fan support under the chosen control assumptions. For bedridden patients, the fan is active during 1929 of 2208 hours, reflecting the higher thermal vulnerability caused by bedding insulation and limited exposed body surface. For staff, fan activation increases to 2092 of 2208 hours, mainly due to higher metabolic heat production.

These results indicate that local fan demand is strongly profile-dependent. Mobile patients require little additional support, while bedridden patients and staff require fan operation during most of the summer period to compensate for the higher cooling setpoint. The results should be interpreted as a conservative control-based estimate of fan electricity use rather than as predicted user behaviour, since actual operation would depend on comfort preference, staff routines, draught perception, and noise.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

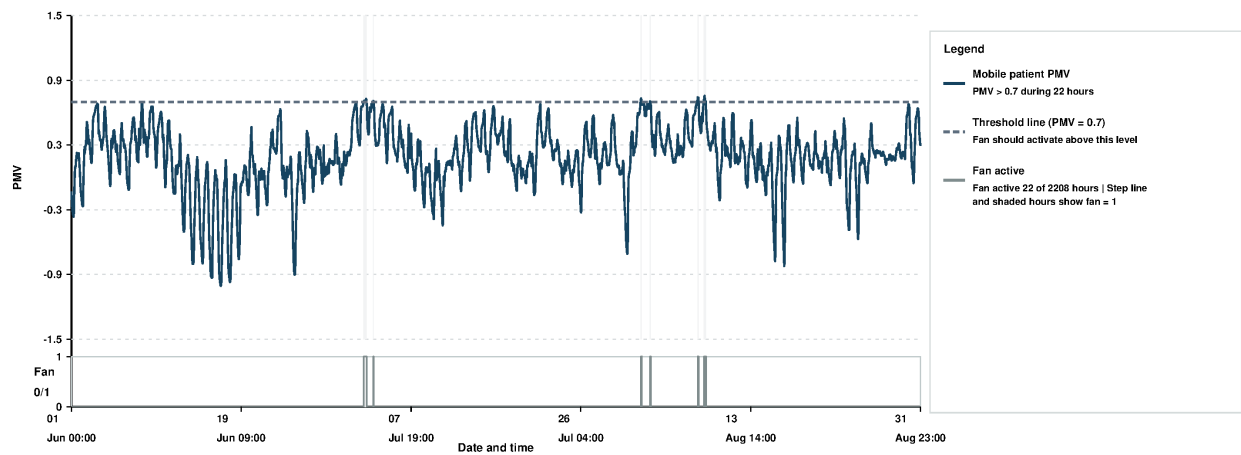


Fig. 4.20: Local fan activation for mobile patients based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.

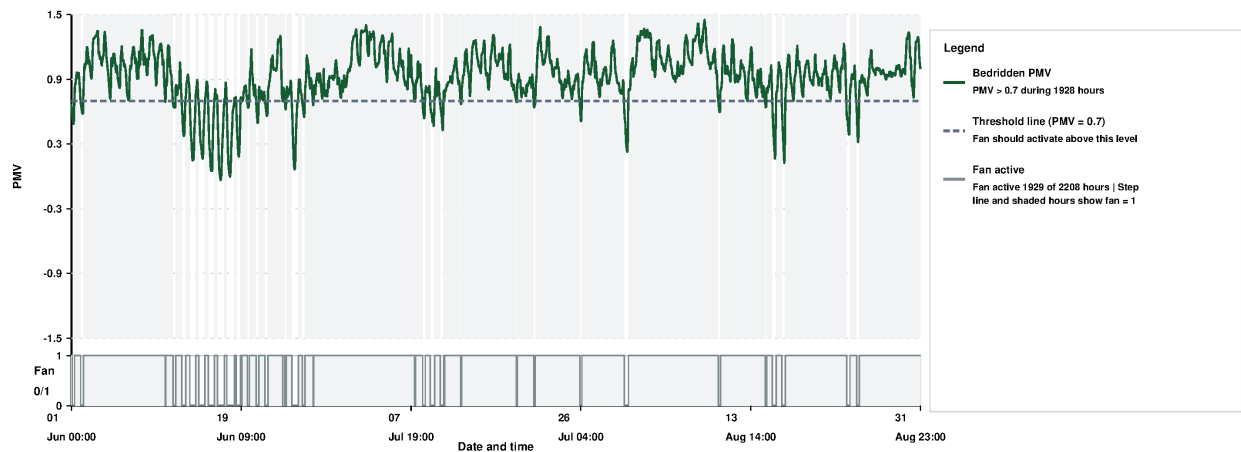


Fig. 4.21: Local fan activation for bedridden patients based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.

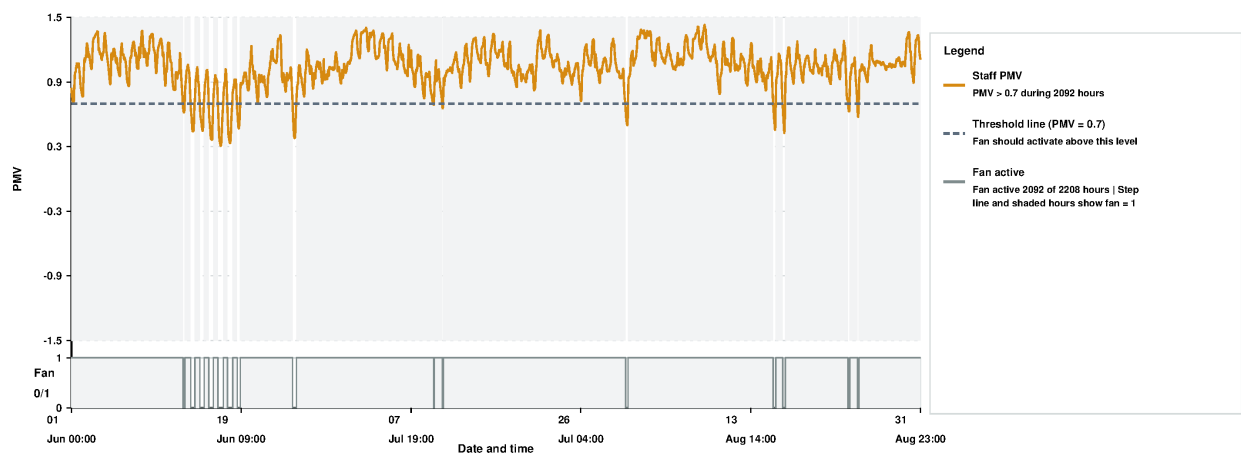


Fig. 4.22: Local fan activation for staff based on PMV exceedance, using a 15 W on/off fan with an air speed of 0.4 m/s.

4.2.5 Hybrid operation: flexible HVAC setpoint

The final scenario evaluates the thermal comfort effect of the hybrid strategy described in the previous section: a mechanical cooling setpoint of 26°C, supplemented by local fan operation when additional occupant-level cooling is required. The resulting SET is compared with the HVAC baseline, which uses a 24°C cooling setpoint without local fan support or passive measures.

For mobile patients, the hybrid scenario remains close to the HVAC baseline, but performs slightly less favourably due to the higher cooling setpoint. The average SET increases from 25.12°C to 25.78°C, while exceedance above the 27°C threshold increases from 0 to 283 hours. This indicates that the baseline already provides acceptable thermal conditions for this user group, leaving limited benefit from additional air movement. Under the tested assumptions, the higher setpoint is therefore only partly compensated by the hybrid strategy.

For bedridden patients, the hybrid scenario reduces average SET from 29.71°C to 28.86°C, but exceedance above 27°C remains almost unchanged, increasing slightly from 2185 to 2187 hours. This shows that local air movement can lower perceived heat stress, but is insufficient to bring this user group below the selected threshold for most of the summer period. The limited improvement is likely related to the high total insulation of the body-bedding system and the reduced exposed body surface, which constrain convective and evaporative heat loss. For this group, targeted air movement may still provide local relief, but requires careful evaluation of draught risk, noise, hygiene and clinical acceptability.

For staff, the hybrid scenario shows the strongest improvement. Average SET decreases from 30.13°C to 27.74°C, while exceedance above 27°C decreases from 2200 to 1760 hours. This confirms that elevated local v_{air} is particularly effective for active occupants with higher metabolic heat production, as increased convective and evaporative heat loss can directly reduce perceived thermal stress. However, the remaining exceedance hours indicate that air movement alone does not fully resolve staff comfort under the tested 27°C setpoint.

Overall, the hybrid strategy shows that local fan-supported air movement can partly compensate for a higher mechanical cooling setpoint, but the effect is strongly user-dependent. The benefit is clearest for staff, moderate for bedridden patients and least favourable for mobile patients. Hybrid cooling should therefore not be interpreted as a uniform room-level solution, but as a targeted comfort strategy that depends on user position, activity level, clothing or bedding insulation and clinical acceptability.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

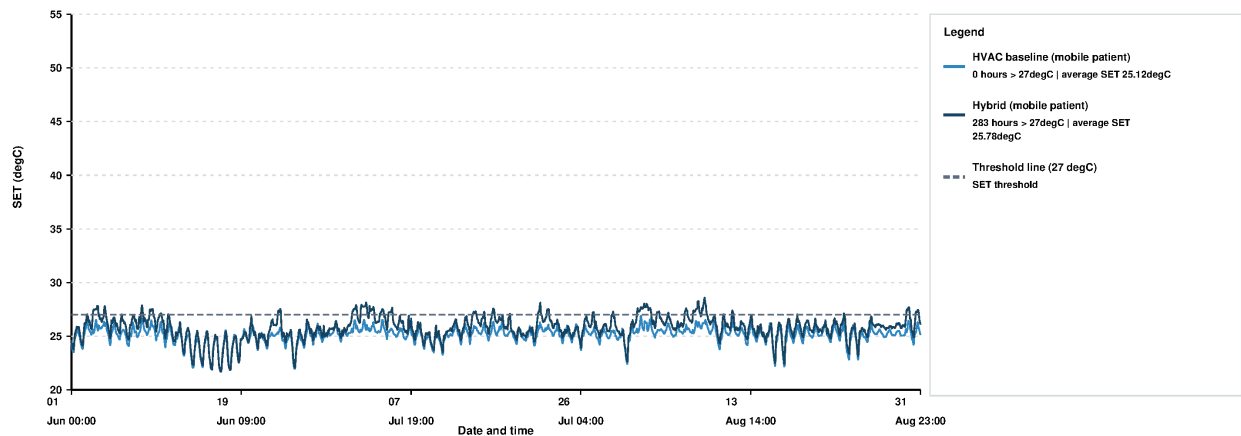


Fig. 4.23: Hourly SET plot over the summer period for the hybrid scenario mobile patient.

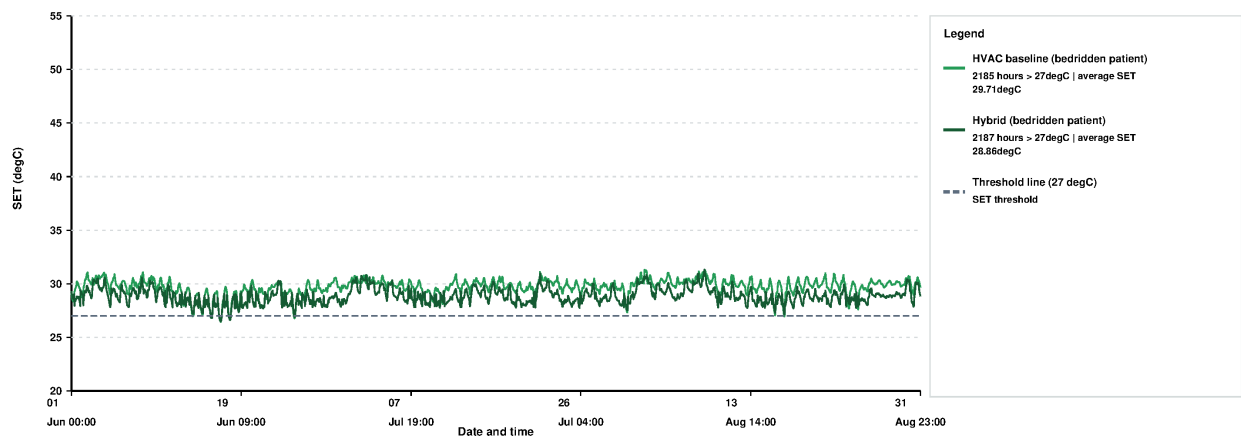


Fig. 4.24: Hourly SET plot over the summer period for the hybrid scenario bedridden patient.

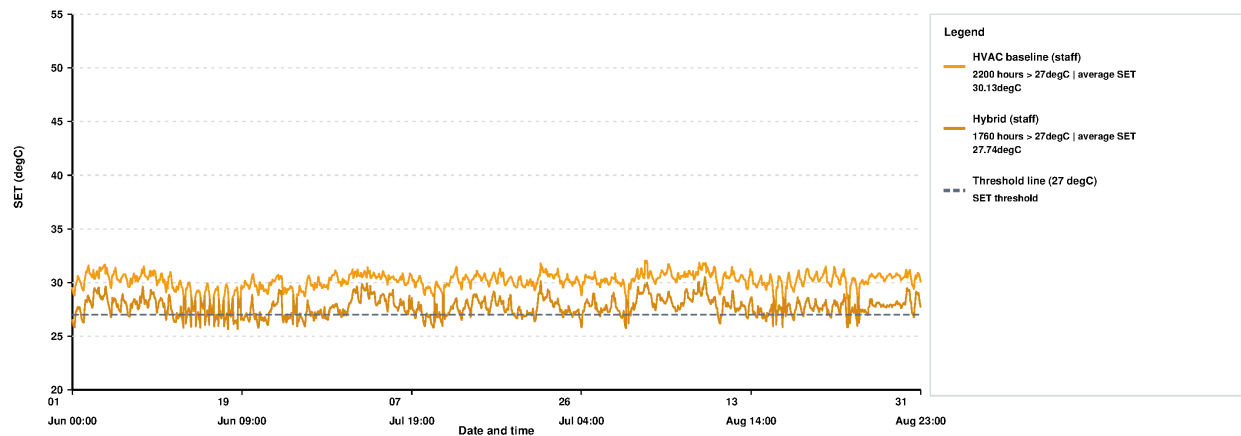


Fig. 4.25: Hourly SET plot over the summer period for the hybrid scenario staff.

4.2.6 Energy and cost reduction with a hybrid operation

Impact on cooling load and energy reduction

Raising the cooling setpoint from 24°C to 26°C substantially reduces the remaining cooling load. In the HVAC baseline, active cooling is required during 923 of 2208 hours (Fig. 4.26), corresponding to an ideal cooling load of 761.29 kWh (Fig. 4.28). In the hybrid scenario, active cooling decreases to 387 hours (Fig. 4.27), with a remaining ideal cooling load of 239.21 kWh (Fig. 4.29). This corresponds to a reduction of approximately 58% in active cooling hours and 69% in ideal cooling load.

These values represent ideal cooling loads, not final electricity use, as discussed below. The EnergyPlus ideal loads approach calculates the heat that must be removed to maintain the setpoint, excluding system efficiency, distribution losses, part-load behaviour and fan electricity use.

The time-series results show that the HVAC baseline requires cooling more frequently and with higher peak loads, while the hybrid scenario produces shorter, less frequent and generally lower-intensity cooling periods. Cooling remains necessary during warmer episodes and periods with higher heat gains, but many moderate-load hours in the baseline disappear once the setpoint is increased.

These results indicate that occupant-level air movement can reduce the mechanical cooling burden by maintaining part of the comfort effect through convective and evaporative heat loss rather than through lower room T_a . The operational energy reduction may differ from the ideal-load reduction, depending on HVAC efficiency and additional fan electricity use. The following section therefore evaluates the balance between reduced cooling load and fan operation.

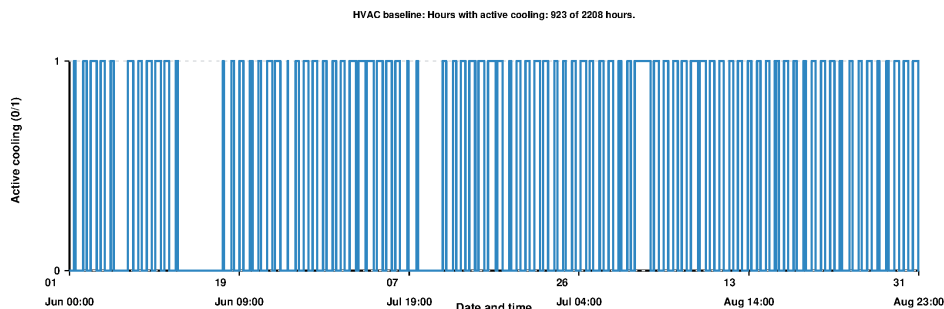


Fig. 4.26: Hourly active-cooling status for the HVAC baseline scenario, where 0 indicates no mechanical cooling and 1 indicates active mechanical cooling.

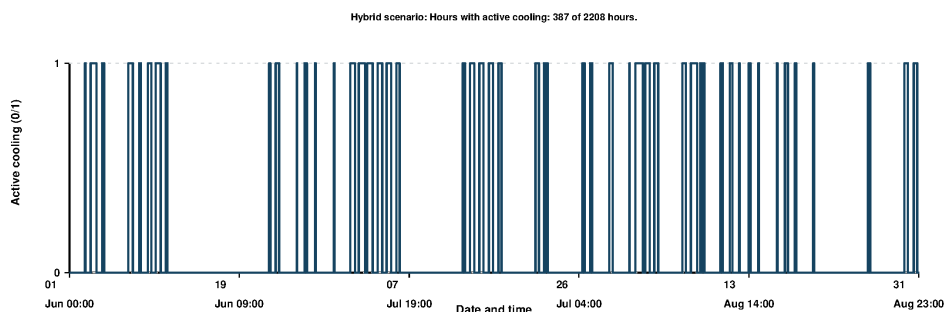


Fig. 4.27: Hourly active-cooling status for the Hybrid scenario, where 0 indicates no mechanical cooling and 1 indicates active mechanical cooling.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

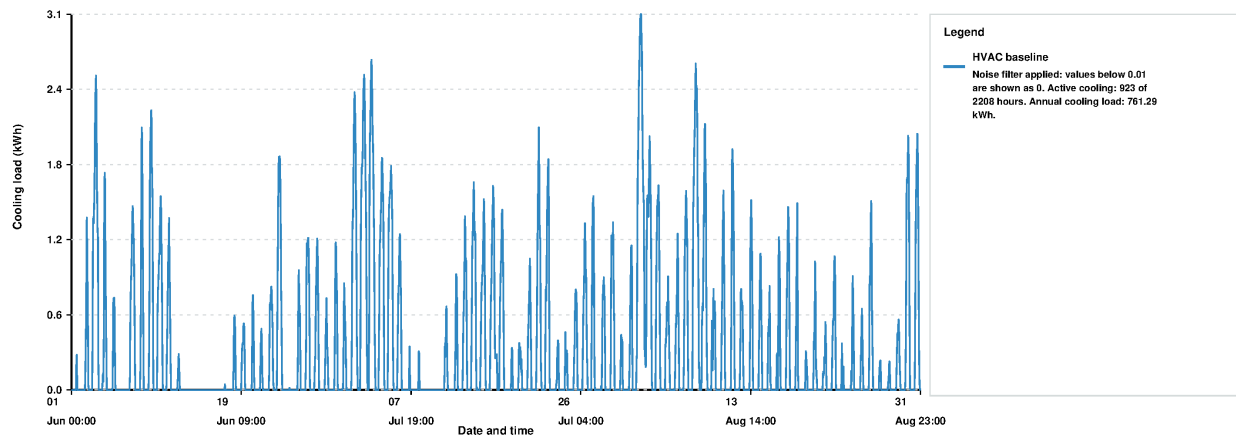


Fig. 4.28: Hourly plot cooling load for the HVAC baseline scenario.

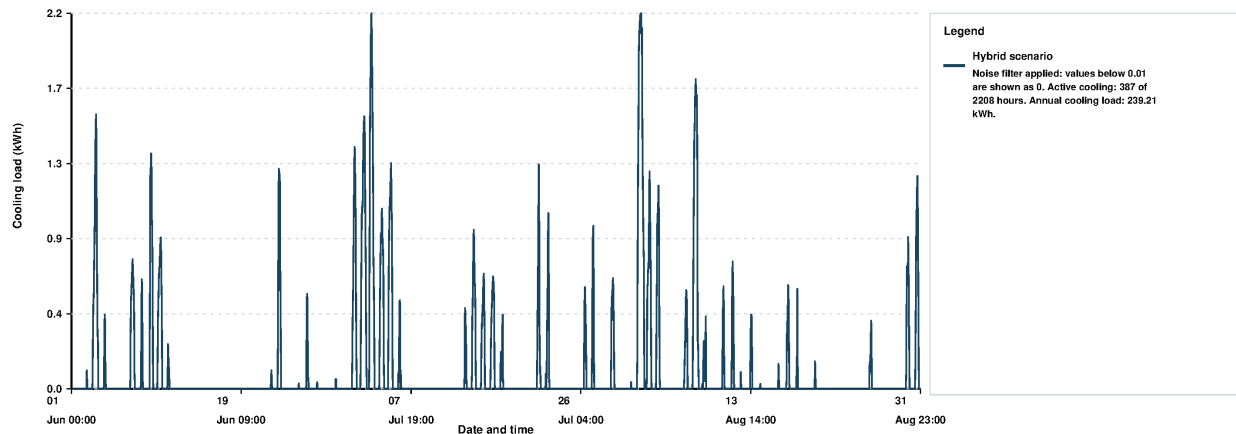


Fig. 4.29: Hourly plot cooling load for the hybrid operation scenario

Impact on cost reduction

The cooling-load results were converted into an indicative electricity and cost estimate. Cooling electricity was calculated by dividing the ideal thermal cooling load by an assumed COP of 4.0, while fan electricity was added directly as electrical consumption. The resulting values are summarised in Table 4.2.

The hybrid strategy reduces cooling-related electricity use from 190.32 kWh to 59.80 kWh, corresponding to a reduction of 130.52 kWh before fan operation is included. After adding the modelled fan electricity use of 60.65 kWh, based on 15 W fans and PMV-based on/off control, the net electricity reduction becomes 69.87 kWh for the analysed summer period. At an electricity price of €0.20–€0.40/kWh, this corresponds to an indicative saving of approximately €13.97–€27.95 per room, or €0.52–€1.04/m² for a 27 m² patient room.

A more realistic implementation may prioritise local fan support for bedridden patients, who remain in a fixed position, rather than for staff moving through the room. Under this assumption,

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

fan electricity use decreases from 60.65 kWh to 29.27 kWh. The total hybrid electricity use would then decrease from 120.45 kWh to 89.07 kWh, resulting in a net electricity reduction of 101.25 kWh compared with the HVAC baseline. This corresponds to an indicative saving of approximately €20.25–€40.50 per room, or €0.75–€1.50/m² for the analysed summer period.

Parameter	Unit	Baseline HVAC	Hybrid scenario	Reduction
Cooling load	kWh thermal	761.29	239.21	522.08
Assumed COP	-	4.0	4.0	
Electricity use for cooling	kWh electric	190.32	59.80	130.52
Fan electricity use	kWh electric	0.00	60.65	-60.65
Total electricity use	kWh electric	190.32	120.45	69.87
Active cooling hours	h	923	387	536

Electricity price	Unit	Baseline electricity cost	Hybrid electricity cost	Net saving
Low tariff	€0.20/kWh	€38.06	€24.09	€13.97
Medium tariff	€0.30/kWh	€57.10	€36.13	€20.96
High tariff	€0.40/kWh	€76.13	€48.18	€27.95

Table 4.2: First-order cost reduction estimation HVAC baseline scenario versus hybrid scenario

4.3 Simulation discussion and limitations

The simulation results should be interpreted as comparative scenario outcomes rather than exact predictions of patient-room performance. The model intentionally simplifies geometry, operation and airflow behaviour to isolate the relative effects of passive envelope measures, natural ventilation and hybrid air movement and to simulate the schematic design phase.

Simplifying geometries

The hospital layout was reduced to a single representative patient room with thermally relevant adjacent spaces and adiabatic boundary conditions, as described in section 4.1. This approach limits computational effort but simplifies interzonal heat exchange with surrounding rooms. In practice, adjacent spaces may dampen temperature peaks and alter cooling demand, meaning that the model may overestimate thermal extremes. A cluster model with multiple connected rooms would better represent these buffering effects.

Bathrooms were not modelled as separate thermal zones but included within the main room abstraction. This is expected to have limited influence on the main passive cooling trends, although moisture loads and local heat gains may be simplified. Interior doors were modelled as closed constructions, which is a more critical assumption for natural ventilation because it excludes corridor interaction and potential cross-flow. As a result, airflow rates and cooling potential may be underestimated in scenarios where open-door or leakage pathways would be relevant.

The façade was simplified by excluding window frames, thermal bridges and detailed material properties. This may slightly overestimate transparent area, solar transmission and daylight availability. External shading was represented as a solar-blocking geometry without detailed surface reflectance, which is acceptable for first-order thermal assessment but less robust for daylight evaluation. The surrounding urban context was not explicitly modelled for daylight because of limited nearby obstruction, while wind exposure was approximated through terrain correction factors. Explicit context modelling would improve accuracy, particularly for low-angle solar exposure and wind-driven ventilation, but would substantially increase model complexity.

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

Analysis period and temporal resolution

The analysis was limited to the summer period from 1 June to 31 August with an hourly timestep. This focuses the assessment on peak cooling conditions but excludes cooling loads outside the summer period, so annual cooling demand is likely underestimated. It also limits evaluation of seasonal trade-offs. For example, smaller glazing ratios or lower g-values may reduce overheating in summer but also reduce passive solar gains and daylight availability in winter. A full-year simulation would therefore be required for final design assessment.

The hourly timestep provides a stable basis for building performance simulation but smooths short-term variations in wind speed, solar exposure and window operation. This is particularly relevant for natural ventilation, where short-term gusts and wind-direction changes may strongly affect local air velocity. Consequently, peak ventilation effects and transient comfort responses are not fully captured. Finer temporal resolution or coupled airflow modelling would reduce this uncertainty, but at the cost of greater computational demand.

Façade optimisation approach

The passive envelope scenario is based on a simplified façade optimisation using solar-angle analysis and geometric reasoning. A multi-variable optimisation with Galapagos was attempted, but computational limitations prevented convergence for the combined parameters of WWR, shading depth, vertical shading and g-value. The selected façade should therefore be interpreted as a heuristic configuration rather than an optimal solution.

This uncertainty is relevant because façade parameters directly affect solar gains, daylight availability and cooling demand. The current configuration may over- or underperform compared with a true optimum, and the reported solar-transmittance reduction may not be achievable while simultaneously satisfying daylight and visual comfort requirements. A staged optimisation or reduced parametric design space would be needed to verify the balance between thermal and daylight performance.

Metabolic rates and clothing insulation values

The model uses fixed *MET*, *CLO* and bedding insulation values for the three user groups. This supports comparability across scenarios but simplifies behavioural and physiological variability. In reality, occupants may adapt through clothing changes, bedding adjustment, posture, fan use, movement through the room or perceived control. These adaptations are not represented.

This assumption is especially influential for bedridden patients. Their simulated comfort response depends strongly on the assumed total insulation of the body–bedding system, including the 48% bed coverage assumption. The results indicate that targeted air movement can reduce perceived heat stress for this group, but SET remains close to or above the threshold for much of the analysed period. A lower bed coverage percentage or different bedding configuration would increase exposed body surface and may improve the effectiveness of convective and evaporative cooling. Conversely, higher bedding insulation would further limit the benefit of air movement.

The same target v_{air} was applied across user groups, although bedridden patients may require more locally directed airflow to achieve a comparable comfort effect. Because these patients remain in a relatively fixed position, local fans could provide a precise comfort intervention. For staff and mobile patients, fixed local airflow assumptions are less representative because these users move through the room.

Airflow calculation and local air-speed uncertainty

Natural ventilation and local v_{air} were represented through simplified pressure-driven calculations and post-processing rather than fully resolved airflow simulation. This was necessary because the EnergyPlus single-node zone model does not calculate spatial air-velocity distributions. The method is suitable for comparing relative ventilation potential between scenarios, but it introduces substantial uncertainty in occupant-level v_{air} .

The airflow calculation relies on simplified assumptions for pressure coefficients, discharge coefficients, air density and wind-profile correction. In reality, these parameters vary with wind direction, façade geometry, surrounding context, opening position and indoor flow patterns. Short-circuiting, stack interaction, turbulence and room-scale jet behaviour are not explicitly resolved.

The method is only partly comparable to a NEN 1087-type assessment. It uses the same physical basis of pressure-driven airflow but applies it dynamically to hourly weather data and simplified façade assumptions. It is therefore useful for evaluating relative temporal ventilation potential, but should not be interpreted as formal ventilation verification. CFD, zonal airflow modelling or coupling with dedicated airflow tools would be required to resolve local velocities, short-circuiting and bed-level airflow more reliably.

Operational assumptions for window use

Window use was modelled through rule-based hourly control. Windows are therefore either open or closed for each hour, whereas real operation is more dynamic and depends on thermal sensation, outdoor temperature, air quality, noise, safety, infection control, staff routines and patient preference. This introduces uncertainty in both the timing and duration of natural ventilation. No distinction was made between day and night operation. In practice, night-time window use may be restricted by safety protocols, clinical routines or acoustic constraints, even though night ventilation can be important for heat removal. The effect of this assumption is context-dependent because ventilation timing determines whether heat is removed before or after thermal peaks occur. Empirical data on window operation in hospital patient rooms would be needed to refine this part of the model.

4.4 Sub-conclusion energy and thermal comfort performance

RQ3: To what extent do passive envelope measures reduce overheating risk in patient rooms under future climate conditions, considering the role of internal heat gains and thermal storage?

The simulation results show that patient-room performance is strongly affected by future climate conditions, user characteristics and the available heat-removal mechanism. Under the morphed 2050 weather file, summer daytime dry-bulb T_a increases from 19.6°C to 22.4°C, global horizontal radiation from 412.0 to 439.6 Wh/m², while wind speed decreases from 4.3 to 3.7 m/s (Fig. 4.5). Compared with the 2025 baseline, this increases average SET by approximately 2.6°C for mobile patients, 1.8°C for bedridden patients and 3.0°C for staff (Fig. 4.6 and 4.7). The result is useful as a comparative climate signal, although the absolute values depend on the selected morphing method and simplified HVAC assumptions.

Regarding passive envelope measures, the simulations show that solar heat-gain reduction is necessary but insufficient as a stand-alone strategy. The passive envelope reduces transmitted solar radiation by approximately 80%, from around 12 to 2.5 kWh/m². However, internal gains from lighting and equipment remain 13.7 kWh/m², meaning that internal heat becomes dominant once solar gains are reduced. Consequently, average T_o remains high, decreasing from approximately 43°C in the free-floating case to 39°C in the passive-envelope case. The internal-load sensitivity analysis

4. ENERGY AND THERMAL COMFORT PERFORMANCE - RESULTS

confirms this mechanism: a 50% reduction in equipment power lowers average T_o by approximately 3.2°C, while reduced occupancy and timber-frame construction have a limited effect. Internal gains therefore primarily shift the temperature level, while the timing of peaks remains governed by external climate conditions.

RQ4: How can occupant-level air movement, through natural ventilation and local fans, improve SET-based comfort for different healthcare users and enable a higher mechanical cooling setpoint?

Regarding occupant-level air movement, natural ventilation improves SET-based comfort only intermittently. The calculated window v_{air} is 0 m/s for 845 hours, corresponding to 38.3% of the analysed summer period. This indicates that openable windows cannot be considered a stable cooling mechanism, as performance depends on wind direction, façade pressure, opening configuration and timing. When v_{air} is included in the SET calculation, the comfort effect becomes visible: for mobile patients, average SET decreases from approximately 31.0°C to 30.1°C, with exceedance hours decreasing from 1981 to 1478. Air movement therefore does not only remove heat from the room, but also modifies occupant-level heat exchange through increased convective and evaporative heat loss.

The hybrid strategy also reduces mechanical cooling demand. Active cooling hours decrease from 923 to 387 hours, while ideal cooling load decreases from 761.29 to 239.21 kWh. This corresponds to reductions of approximately 58% in active cooling hours and 69% in ideal cooling load. After conversion to electricity using a COP of 4.0 and inclusion of 60.65 kWh fan electricity, the net electricity reduction is 69.87 kWh for the analysed summer period. This corresponds to an indicative saving of €13.97–€27.95 per room. If local fan support is applied only to bedridden patients, which is more realistic than assigning fixed fans to mobile staff, fan electricity decreases to 29.27 kWh and the net electricity reduction increases to 101.25 kWh, corresponding to approximately €20.25–€40.50 per room.

Overall, the simulations indicate that passive envelope measures reduce external heat gains but cannot sufficiently control overheating under high internal loads and continuous occupation. Natural ventilation provides useful but unstable occupant-level cooling, while local fans make air movement more controllable and can support higher mechanical cooling setpoints. However, the comfort and energy effects are user-dependent and should be interpreted with substantial uncertainty, given the simplified airflow calculation, fixed user profiles, ideal-load HVAC approach and assumed fan-control logic. The resulting design implication is that patient-room cooling requires a layered strategy: solar control, internal-load reduction, thermal storage management and targeted air movement, combined with moderate mechanical cooling rather than reliance on a single passive measure.

5

IMPLEMENTATION BARRIERS & DRIVERS

This chapter examines how passive and hybrid cooling strategies can be implemented in healthcare design practice. Based on stakeholder interviews, it identifies key barriers, drivers and design-process conditions, and translates these findings into design implications and recommendations for early-stage hospital design.

5. IMPLEMENTATION BARRIERS & DRIVERS

5.1 Stakeholder interview objective and methodology

Semi-structured expert interviews were conducted to complement the simulation analysis and examine the implementation conditions for passive and hybrid cooling strategies in Dutch hospitals. The interviews focused on organisational, technical and comfort-related factors influencing adoption in standard low-risk patient rooms.

Participants were selected based on their involvement in healthcare design, decision-making, operation or performance assessment. The sample included healthcare architects, clients and developers, hospital technical specialists, building services consultants, building physics consultants, indoor environmental quality experts and thermal comfort specialists. In total, 10 interviews were conducted, of which six respondents were directly involved in the case-study project and four acted as external hospital-design experts.

Each interview followed a two-part structure. The first part was semi-structured and addressed current cooling and ventilation practice, passive cooling experience, thermal comfort governance, user differentiation, risk management and design-process integration. The second part consisted of a structured card-ranking exercise in which respondents ranked predefined implementation barriers and drivers while thinking aloud. This combined qualitative reasoning with indicative comparative data on stakeholder priorities. The full interview protocol is provided in Appendix O.

Interviews lasted 45–60 minutes, were mainly conducted in person, recorded with informed consent and analysed anonymously. As all participants were Dutch, the interviews were conducted in Dutch; quotes used in this chapter were translated into English, with the original Dutch quotations provided in Appendix Q.

The analysis combined thematic analysis with interpretation of the ranking exercise. The ranking results are treated as indicative rather than statistically representative, due to the limited and uneven sample size, stakeholder diversity and ordinal nature of the method. Their value lies in identifying recurring barriers, drivers and differences in stakeholder priorities. Respondents are referred to using role-based abbreviations throughout the chapter and data is handled according to Appendix P.

- A** Architect
- T** Technical specialist
- B** Building physics expert
- H** Healing environment expert
- I** Installation specialist
- C** Thermal comfort expert

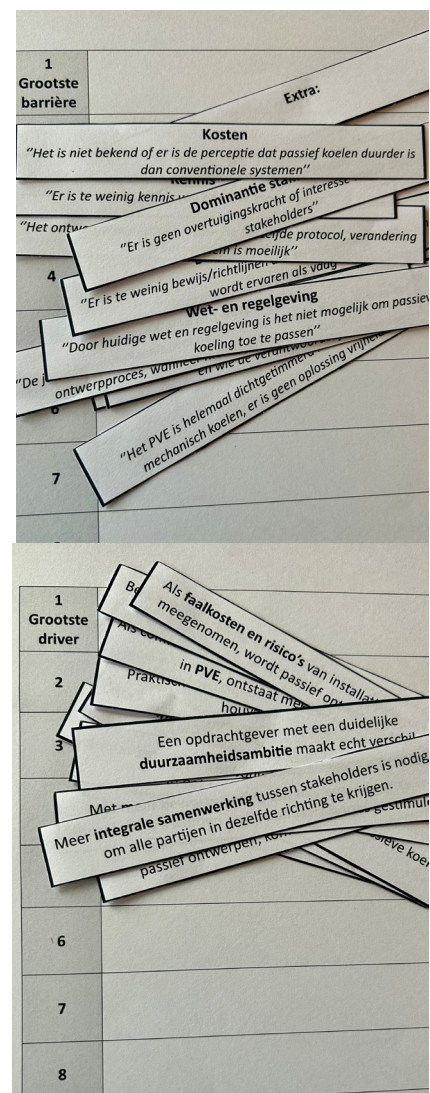


Fig. 5.1: Interview cards for relative ranking and think-out-loud exercise

5.2 Qualitative interview results

5.2.1 Thermal comfort: from system compliance to occupant-centred comfort

Comfort is currently managed through system compliance

In current hospital operation, thermal comfort is primarily managed through the building management system. For patient wards, a summer setpoint of approximately 24°C is used, with limited exceedance hours, while relative humidity is partly driven by equipment requirements, with a target around 30% (T). Monitoring is mainly based on sensors and focuses on parameters such as temperature, CO₂ and solar radiation, although more variables could technically be monitored (I; T). This reflects a system-oriented comfort approach over a complaint-based one. As stated: *“The risk of a complaint-based system is that people may start reporting issues that are not actually technical problems. If the room is 24 °C and I personally do not find it comfortable, I may report it as a complaint, while the system indicates that the conditions are within the required range.”* (T).

Thermal comfort varies between users and over time

Thermal comfort in healthcare environments is influenced by individual and temporal factors. Comfort perception varies between users and changes over time, with seasonal adaptation playing an important role as illustrated by the thermal comfort expert: *“You can see that in the later period of 2025, people were most accustomed to the heat. As a result, a room temperature was perceived as cooler than at the beginning of the summer, and also compared to 2024.”* (TC). This indicates that there may also be physiological adaptability as we become more accustomed to warm environments.

Adaptive capacity is limited and user-specific in healthcare settings

Thermal comfort should be considered in relation to physiological, psychological and behavioural adaptive capacity (C). In healthcare environments, these capacities differ strongly between user groups. Patients may have limited ability to adapt through behaviour, clothing or movement, while staff experience different thermal conditions due to activity level and work patterns. For example, staff performing sedentary tasks, such as office work, may experience colder conditions more quickly (H). This makes uniform comfort requirements difficult to define.

Although seasonal adaptation and user differences are recognised conceptually, they are not consistently translated into design or operation. Different seasonal setpoints are not systematically applied, despite their relevance for adaptive comfort (C). As a result, hospital comfort strategies remain largely based on fixed system criteria.

Thermal comfort is part of the healing environment, but not yet fully embedded in design

Thermal comfort should be understood as part of a broader healing environment, where stress reduction, positive distraction and patient well-being also play a role (H). However, this broader understanding is not yet sufficiently integrated into current design processes. From a building services perspective, user-oriented comfort receives limited attention: *“From a building services perspective we are not sufficiently engaged with this yet; there is still a lack of knowledge.”* (C). Requirements are often formulated from a maintenance or operational perspective rather than from user needs (H).

In the SPOT case, patient-level comfort was not yet explicitly assessed in the schematic design phase; comfort was primarily considered at building scale. This suggests that occupant-centred comfort may enter the process too late to influence early spatial and façade-related decisions (A4).

User control is valued, but its actual effect remains unclear

Current practice does provide some degree of individual control: patients can adjust temperature, solar shading and lighting, while staff can control temperature and solar shading (T). However, it remains unclear whether these systems substantially influence the indoor environment or mainly function as perceived control (H). At the same time, survey results from Erasmus staff indicate that the ability to personally control the indoor climate is highly valued by users (H). This suggests that control should be treated as a comfort variable in itself, not merely as an operational feature.

5.2.2 Barriers: why passive strategies fail to become decisive

The interviews indicate that the implementation of passive cooling is constrained by a set of interacting barriers rather than by one dominant technical limitation. The barriers below summarise the main mechanisms through which passive strategies lose influence during the design process.

Clinical uncertainty and installation-driven thinking favour mechanical control

Hospital design is strongly shaped by clinical risk aversion and an installation-driven logic. Passive strategies are difficult to implement because they introduce uncertainty regarding comfort, air quality, infection prevention and operational reliability (C; T; A2; B1; A4). In clinical settings, such uncertainty is rarely accepted as a design condition. It instead reinforces the preference for mechanically controlled systems, higher ventilation rates and clearly accountable performance. Infection prevention was repeatedly identified as a decisive constraint, as it remains difficult to demonstrate that alternative ventilation concepts do not increase clinical risk (T).

This risk-averse logic is reinforced by the increasing reliance on medical technology and building services, which has partly shifted healthcare environments away from more natural or healing-oriented design principles (A1). As the technical specialist stated: *“In healthcare, the passive approach actually seems to be declining.”* (T). From an installation perspective, design calculations often start from a worst-case baseline rather than from passive potential: *“Ideally, we would also prefer to start with passive design. However, in practice, calculations often begin without accounting for passive measures, using a kind of worst-case scenario. The question then becomes whether the required installation capacity can still be accommodated in the building. Especially in a phase where technical space has to be negotiated with the architect, that worst-case scenario becomes the starting point.”* (I). This explains why one architect characterised hospitals as *“installation-monsters”*, where fully passive approaches are difficult to implement (A2).

Consequently, even technically simple passive measures become complex in healthcare environments. They must be evaluated not only as building-physics interventions, but also against comfort, hygiene, maintenance, operational control and clinical accountability requirements (H; I; T).

Short-term cost logic weakens long-term passive value

Financial constraints and short-term investment logic also form a barrier to passive strategies (A1; I; T; A3; A4). A shift in construction costs is taking place, with an increasing share allocated to installations. Whereas the division between building and installations is currently approximately fifty-fifty, the installation share is moving towards 60% of total construction costs (T). As one respondent noted: *“As a rough estimate, the construction cost of a hospital is around €3,000 to €3,200 per square metre. Depending on the project, the share of building services can be around €1,500 to €1,600 per square metre.”* (I).

Passive measures often require upfront investment in façade design, solar shading, modelling or coordination, while the benefits appear later through lower cooling demand, reduced operational costs or improved comfort. Respondents noted that additional mechanical cooling can appear financially simpler when active systems are already included in the project (I; T). Although TCO calculations are considered useful, they do not yet consistently translate long-term operational savings into increased upfront budget (I; T; A4).

The current economic logic also favours mechanical cooling because it remains relatively cheap to apply compared to more structural passive interventions (I; T). Installation budgets in hospitals are substantial, but this does not automatically make passive alternatives easier to justify. Passive measures only become financially persuasive when they allow a substantial reduction in mechanical systems. If the active system is already included, a limited increase in cooling hours is often perceived as cheaper than additional investment in architectural or passive measures (A4).

Fragmented requirements and hospital loads constrain passive design

The Programme of Requirements can unintentionally limit passive design when requirements are fragmented, overlapping or formulated as technical solutions rather than performance ambitions (I; A2; A3; A4). In healthcare projects, multiple stakeholders contribute requirements from different professional perspectives, which can lead to inconsistent values or conflicting interpretations. As a respondent stated: *“Everyone is aiming for the same ambition, but in practice you see many different requirements and values appear. The Programme of Requirements often contains requirements that essentially express the same objective, but are interpreted or written down slightly differently.”* (I). Although the Programme of Requirements can evolve and support user-driven outcomes (A3), fragmented or solution-oriented requirements may reduce design freedom and reinforce conventional installation-led assumptions (I; A2).

This is particularly relevant because hospital programmes and internal heat loads strongly affect passive cooling potential. Equipment, lighting, occupancy and medical technology can dominate the room heat balance, reducing the relative effect of solar-control measures alone (A1; I; T). These assumptions are often already fixed before installation design starts, making them difficult to reconsider later. Technical specialists confirmed that solar gains may form only a limited part of the total thermal load in patient rooms: *“The sun may feel like a major heat source, but when you see how much equipment is brought into some patient rooms, it only accounts for about a quarter.”* (T). This validates the findings from the simulation.

Institutional routines and system complexity limit design change

Decision-making in hospital design is strongly shaped by institutional continuity, risk aversion and established operational routines. Healthcare institutions are often perceived as conservative, making it difficult to approach new projects differently from previous ones (A1; A4; I). This was explicitly noted in relation to SPOT: *“The pitfall is to say: ‘At Erasmus, we have always done it this way, so we want SPOT to be designed in the same way.’ That may be possible, but technology is developing, the building is different, and its use may also differ from the existing central location.”* (I).

This tendency is reinforced by increasing system complexity and reduced operational control. Passive and hybrid strategies require confidence in how the building will be operated, maintained and adjusted over time. However, respondents described healthcare buildings as increasingly complex, outsourced and difficult to intervene in practice (A2). As a result, deviations from standardised mechanical systems, such as operable windows, natural ventilation or local airflow, are often perceived as risky (H; T; I; B1). One architect summarised this loss of agency as follows: *“We have lost control over our own buildings; everything is outsourced and has become so complex that we are not even allowed to touch them due to warranty considerations.”* (A2).

Fragmented responsibilities reinforce risk-averse decision-making

The construction process itself reinforces cautious decision-making because responsibilities are distributed across many actors. As stated: *“In construction, everything consists of many interconnected links. Each party is responsible for one part of the process, and control and certainty are always important.”* (C). Although design teams may formally be organised in an integrated way, this does not automatically result in integrated decision-making in practice (C).

Generic hospital flexibility suppresses differentiated passive solutions

Hospitals are often designed as generically as possible to allow future functional changes (T; I). This limits passive cooling, because passive strategies usually depend on specific relationships between function, orientation, façade, internal loads, airflow and user needs. When multiple healthcare functions are combined in one building, the most demanding or vulnerable function can determine the climate concept for wider areas (T). This reduces the opportunity to apply passive strategies

selectively in lower-risk or office-like zones where they may be more feasible (TS; A3). *“Hospitals are designed as generically as possible. Medium care and high care are therefore almost the same, while ICUs and isolation rooms are treated as separate units.”* (T)

Early constraints and uneven expertise limit passive potential

Passive cooling potential is strongly affected by early decisions on orientation, massing, façade design, spatial layout and programme distribution. In practice, these decisions are often constrained before passive performance is assessed, due to urban planning, municipal façade expectations, project phasing or predefined technical assumptions (I; A1). In the SPOT case, the fixed plot, south-west orientation and polluted urban context further reduced the perceived feasibility of natural ventilation and façade-based passive measures (I; T). As one respondent noted: *“In SPOT, there are many additional constraints related to the urban design plan. The Municipality of Rotterdam is involved and has a specific vision for the façade. This does push the design in a certain direction.”* (I).

This timing issue is reinforced by uneven knowledge distribution across stakeholders. Architects generally showed a stronger understanding of passive strategies, while this knowledge was more limited among clients and building services engineers (A1; I; A4). As a result, passive measures are not always part of the shared design framework from the start.

Technical expertise is also not consistently involved early enough to influence fundamental passive design choices. Building physics consultants may only be consulted once performance problems have already emerged: *“Sometimes they are only involved when a problem occurs.”* (A1). Similarly, installation advisors often enter after the PvE has already fixed assumptions about occupancy, equipment loads and climate requirements, making it the starting point rather than an open design space: *“We become involved after the PvE, when climate requirements such as expected occupancy, equipment loads and internal heat gains have already been defined. That is simply where we start.”* (I).

Regulation and assessment frameworks provide limited support for passive-first design

Formal building regulations were not consistently perceived as the main barrier (B1), but the absence of explicit passive-performance requirements makes passive strategies easier to discard as stated: *“If it is not included in regulations, it becomes more difficult and is often the first to be discarded.”* (C; A3). Respondents also indicated that current assessment frameworks, such as BENG and MPG, do not fully reward passive design principles, which can reduce their competitiveness in tenders (A2). In hospitals, the stronger regulatory barrier often comes from clinical requirements rather than building regulations, particularly where infection prevention conflicts with natural ventilation or reduced ventilation rates (T).

Limited climate robustness and urgency delay innovation

Current design criteria appear to focus primarily on technical operating limits rather than long-term climate robustness. For SPOT, the design considers an extreme condition of 34°C and 70% relative humidity, representing the boundary at which equipment must remain operational. However, no specific future climate year or weather dataset was included in the assessment (T). This suggests that future overheating risk is addressed mainly through predefined technical design values, rather than through explicit climate scenario analysis.

This limited future-oriented assessment is reinforced by a broader lack of urgency for changing established design approaches. As one respondent stated: *“Something has to go wrong to create a sense of urgency.”* (A1). The implementation challenge is therefore not only technical, but also behavioural and organisational.

5.2.3 Implementation drivers / enabling conditions

The interviews indicate that passive cooling requires more than technical feasibility. Successful implementation depends on a set of enabling conditions that make passive strategies visible, credible and actionable within the design process.

Passive-first design requires explicit ambition and accountable ownership

A strong and explicit project ambition is essential to prevent passive strategies from becoming secondary to conventional installation-based solutions (H; A2; I; B1). General awareness of overheating or installation dependency is insufficient; passive cooling must be formulated as a design ambition before the PvE and climate concept translate project goals into fixed technical assumptions. Without such ambition, passive measures are unlikely to survive later cost, risk and coordination pressures. As one respondent stated: *“Ownership and responsibility is where it all starts. If you have someone who does not have that, or a client who does not have it or does not value it, then no matter how much you argue or try, nothing will happen.”* (A1)

This ambition also requires an identifiable actor who actively defends passive strategies throughout the design process. Because passive measures depend on early spatial decisions, performance evidence and cross-disciplinary coordination, they are easily deprioritised when no one is responsible for keeping them on the agenda (A1; A2). This role may be taken by an architect, client representative, building physicist or sustainability lead, but it must be explicitly assigned. Architects can be particularly influential because they mediate between technical constraints, client ambitions and future-oriented design thinking: *“Sometimes you have to show clients or stakeholders a point on the horizon; people reason from the here and now, from how things are and how they currently work and experience them. But our task is also to show how it could be in the future.”* (A1)

However, disciplinary influence affects whether passive strategies remain decisive. If performance issues can still be compensated through building services, architectural arguments may carry more weight than installation-related concerns: *“As long as the issue can still be solved through building services, the installation advisor has less influence than the architect. Architectural arguments are often given more weight.”* (I). However, disciplinary influence appears to be phase- and issue-dependent. While architectural arguments may carry weight in spatial design decisions, respondent A4 indicated that installation advisors become highly influential once overheating or ventilation is framed as a technical risk. In such cases, architects often lack the quantitative evidence needed to challenge the claim that additional mechanical cooling is required.

Early interdisciplinary cooperation is needed before passive options become constrained

Passive strategies depend on the interaction between façade, spatial layout, installations, comfort, infection prevention and operation. Therefore, architects, building physicists, installation advisors, clinical stakeholders and facility management must be aligned before key assumptions are fixed (A2; I; T; A4). Early cooperation is especially important because infection prevention can later overrule technically favourable low-energy solutions if clinical concerns have not been integrated from the start. *“You have to accept that you do not have complete freedom in spatial layout; there is an inherent logic and airflow structure that must be accommodated.”* (A2)

Healthcare function and risk profile determine passive cooling potential

The feasibility of passive cooling depends strongly on healthcare function, clinical risk and user exposure. Respondents indicated that passive strategies are more applicable in lower-risk areas, such as outpatient clinics, offices, support buildings and other functions with less stringent clinical control requirements (A3; T). This suggests that passive cooling should not be assessed at whole-building level, but differentiated by function and risk profile.

5. IMPLEMENTATION BARRIERS & DRIVERS - RESULTS

Healthcare typology further affects comfort requirements. Hospitals and long-term care facilities differ in exposure duration, user adaptation and operational risk. Hospitals generally have shorter stays and higher patient turnover, while long-term care facilities involve prolonged occupancy and stronger relevance of individual comfort preferences (C). Long-term care may therefore offer more favourable conditions for passive strategies due to lower internal loads and greater adaptive potential, although longer exposure also increases the impact of overheating. In these settings, passive design should address not only peak temperature reduction, but also personal control, night-time cooling and long-duration comfort (C).

These findings indicate that passive cooling should not be translated as a generic healthcare strategy. Instead, passive potential should be assessed across typologies and sub-functions, distinguishing between highly controlled hospital spaces, standard patient rooms, outpatient areas, offices, support buildings and long-term care environments (A2; A3; T; C). This differentiated approach prevents passive strategies from being rejected because they are unsuitable for the most critical spaces, while still allowing them to be applied where comfort requirements, risk profiles and operational conditions are more favourable.

The PvE must be flexible and performance-based enough to allow passive solutions

A flexible and coherent Programme of Requirements is a key driver for passive implementation (A2; I). Instead of translating ambitions too early into fixed technical solutions, the PvE should define performance targets, comfort ambitions and risk categories. This allows passive strategies to be tested as possible ways to meet requirements, rather than being excluded by predefined system assumptions. Consistency in requirement formulation is also essential, because fragmented requirements can undermine a shared ambition (I).

Passive strategies require credible evidence and benchmarks to become acceptable

In the Erasmus MC context or other university hospitals, passive strategies need strong evidence before they can influence decisions, particularly when they deviate from standard practice (T; A1; A4; B1). Scientific substantiation, simulation results, benchmarks and reference projects can help translate passive concepts into defensible design decisions. *“The Erasmus MC context was described as highly sensitive to research-based evidence.”* (T) A4 added that evidence is not only required for energy or comfort performance, but also for broader claims around the healing environment. Although architects may consider healing environment principles important, these arguments remain difficult to use in decision-making when their benefits are insufficiently substantiated.

Total cost of ownership must be connected to actual budget decisions

TCO can support passive strategies by making long-term value visible, but only if operational savings and reduced system dependency are allowed to influence upfront investment decisions (A1; I; T). Without this link, passive measures remain disadvantaged because they often require early investment while benefits occur later. TCO should therefore be used as a decision criterion, not only as a calculation exercise. *“We are expected to carry out TCO calculations. However, in practice these are often only used to assess direct investment measures. What you see is that operational or management-related savings do not necessarily lead to an increased upfront budget.”* (I)

The right execution partners must be selected for low-tech or installation-light concepts

Successful implementation also depends on whether the construction team can execute non-standard passive strategies reliably (A2). Low-tech, installation-light or bio-based concepts may require different expertise than conventional hospital construction. If capable contractors or suppliers are not available, passive concepts become harder to realise and are more likely to be replaced by standard technical solutions. *“Identifying capable contractors remains challenging, particularly when combining low-tech or installation-light approaches with bio-based materials.”* (A2)

Passive-first design requires a different sequencing of assumptions

A passive-first approach requires a different order of reasoning. Instead of starting from worst-case mechanical capacity, design should first define user needs, risk profiles and passive potential, after which active systems address the remaining performance gap. This contrasts with current practice, where installation design often starts from ensuring that sufficient technical capacity and space are reserved from the outset (A1; I). A respondent stated: *"current cost-reduction logic could be reversed. Instead of cutting architectural measures when budgets become constrained, design teams could investigate whether smarter architectural choices reduce the need for mechanical systems. This would require passive strategies to be evaluated before installation capacity is fixed."* (A4)

Simulations should test realistic reduction of system dependency

Simulations should not only evaluate ideal passive scenarios, but also reflect the conservative design logic of hospital projects. Since hospital climate design often starts from mechanical capacity, generic functionality and worst-case assumptions, passive scenarios should test how much system dependency can realistically be reduced without compromising reliability (I; T).

5.2.3 Natural ventilation and fan operation

Openable windows create a tension between psychological value and system control

Operable windows remain a recurring point of discussion. They are valued for their positive contribution to patient well-being and psychological comfort (A3; H; A4), yet they also raise concerns about controlled indoor conditions (A1; H; I; T; A4). Mechanically ventilated systems are often considered more reliable for air quality, and a common argument is that *"operable windows disrupt building services systems"* (A1). Technical specialists did not identify a clear physical contribution of openable windows to indoor climate improvement in patient environments, except for their psychological value, as opening windows may increase room temperature and disturb controlled operation (T). As stated: *"What you want to avoid is a situation where, from a user-experience perspective, you want a window to be openable, while at the same time the ceiling system or another system is actively cooling the room. From an energy perspective, that is simply wasteful. Especially in a building that operates 24/7, you want to prevent this kind of conflict, because it can also prevent the building from cooling down again at night."* (I). This indicates that openable windows require explicit control logic rather than being treated as independent passive elements (I; T).

Infection prevention dominates the acceptability of natural ventilation

In clinical environments, infection prevention emerged as a dominant stakeholder in determining whether natural ventilation or low-air-change concepts are acceptable (T). A technically favourable solution can still be overruled by clinical risk perspectives (A4). A respondent stated in an example that radiant cooling was selected because it was cheaper, more energy-efficient and provided better comfort, but was later challenged by infection prevention because a higher ventilation rate was required (T).

Local air movement has comfort potential, but clinical reliability remains contested

Increased air movement was identified as a promising occupant-level comfort strategy. From a comfort perspective, fans can support thermal comfort at higher temperatures: *"A fan can be a good addition to improve thermal comfort, but users need to get accustomed to it."* (C). Localised solutions may be particularly relevant for bedbound patients: *"A bed fan could be a good local solution for bedridden patients. In that case, it is not problematic if there is a risk of draught, as users can adjust it themselves."* (C). However, technical specialists expressed concern that local filtered airflow around the breathing zone would still mix with room air, reducing reliability (T). As stated, *"We prefer to keep outdoor air outside."* (T).

5. IMPLEMENTATION BARRIERS & DRIVERS - RESULTS

The relevance of local air movement is strengthened by the wide variation in patient needs and comfort responses. As stated: *“One should not focus too narrowly on defining a specific patient range; rather, it is clear that this range is very broad, meaning solutions should be adaptable to individual needs.”* (C). This suggests that fan operation, local airflow and other user-level strategies should prioritise adaptability and individual control.

Simulation should include airflow containment, air quality and perceived control

Future evaluation of natural ventilation and fan operation should go beyond thermal comfort effects alone. For openable windows, simulations should assess interaction with active cooling, heat gains, night-time recovery and control logic (I; TS). For local air movement or filtered airflow, assessment should also include airflow containment, mixing, air quality and perceived controllability (C; T). This is necessary to distinguish between psychological benefit, measurable thermal performance and clinical acceptability.

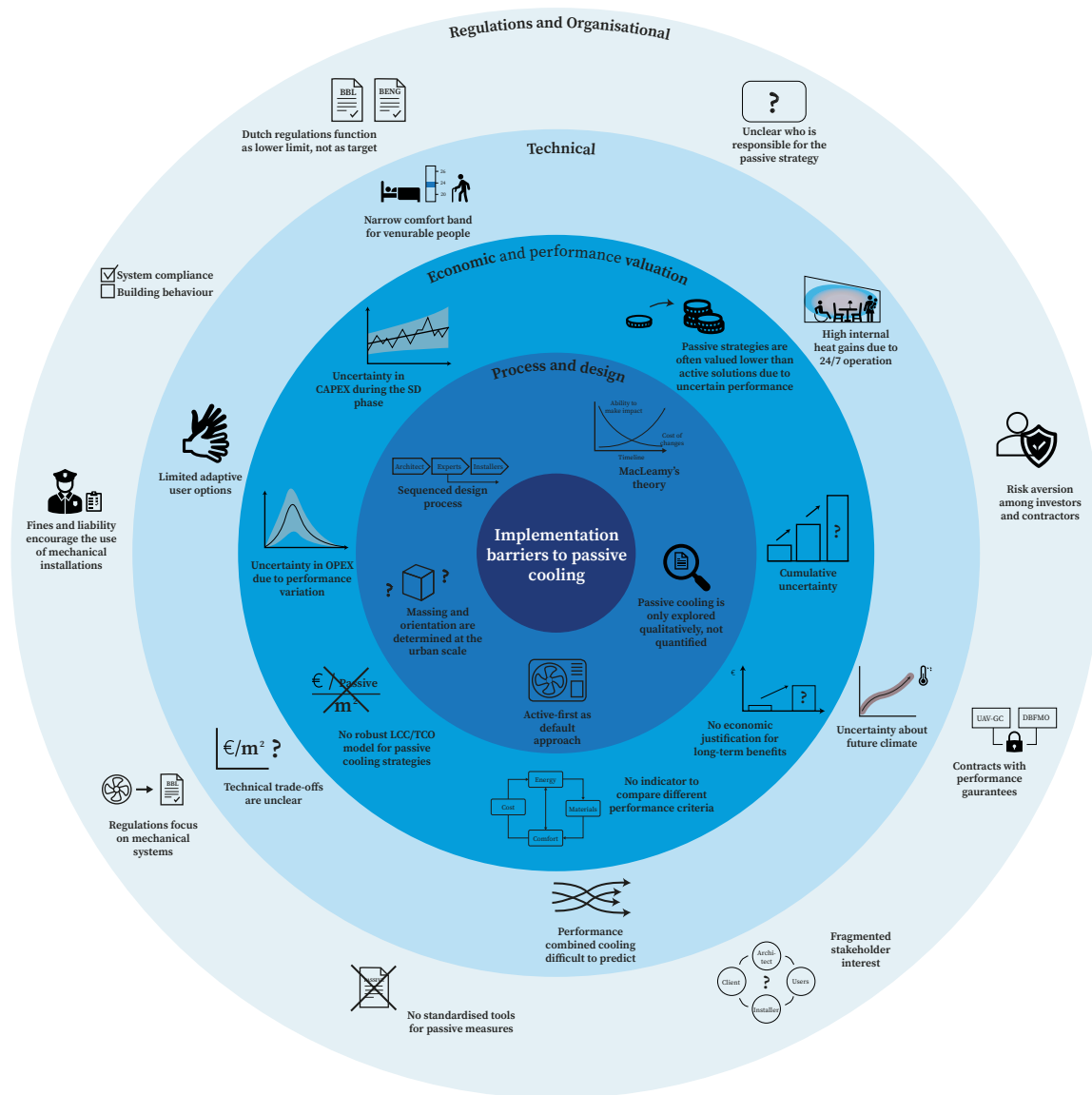


Fig. 5.2: Summary diagram of implementation barriers from the qualitative interview results. (Author's work)

5.3 Quantitative interview results

5.3.1 Indicative prioritisation of barriers and stakeholder variability

Fig. 5.3 shows how respondents prioritised implementation barriers. The results should be interpreted as indicative rather than statistically robust, due to the limited and uneven sample size, differences in stakeholder background and the ordinal nature of the ranking method. Nevertheless, the spread in the ranking is valuable, because it shows not only which barriers were considered important on average, but also where stakeholder perspectives diverged. Appendix O contains more information about the barriers and drivers displayed on the x-axis of Fig 5.3 and 5.4. Appendix R shows rankings per stakeholder.

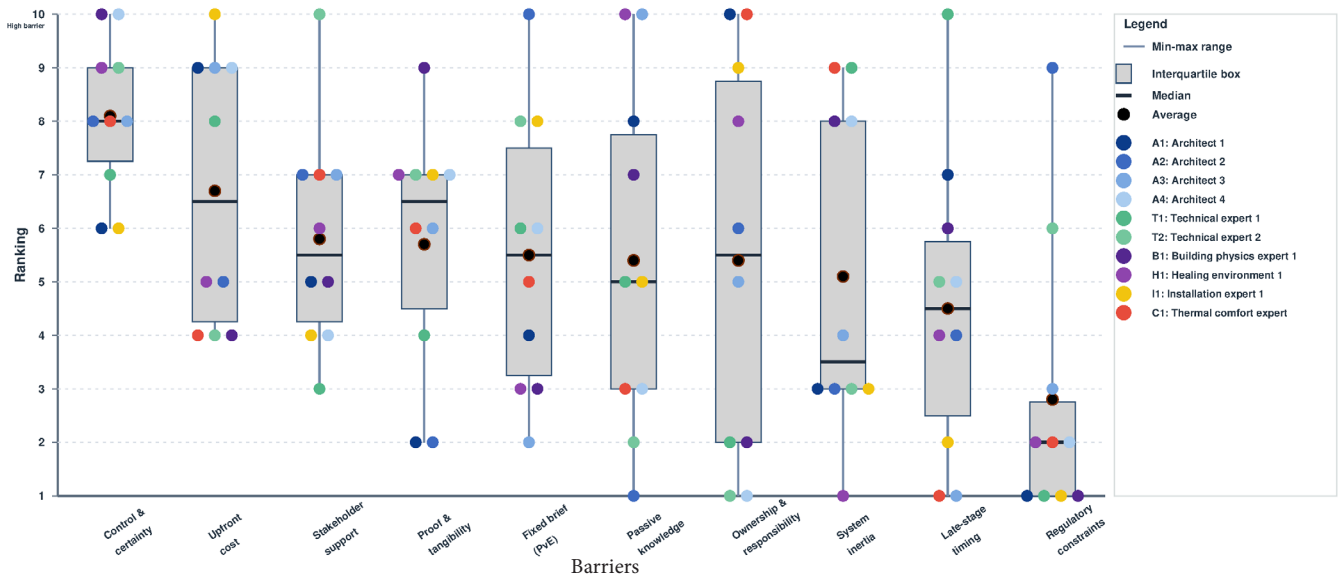


Fig. 5.3: Box plot showing the relative ranking of implementation barriers.

Control and uncertainty were ranked as the most important barrier on average, with relatively strong agreement across respondents. This supports the qualitative finding that passive cooling in healthcare is mainly constrained by concerns about predictability, infection prevention, system reliability and operational control. By contrast, barriers such as knowledge, ownership, and system-related barriers show greater variation, indicating stronger dependence on stakeholder role and position within the design process.

Cost also ranked relatively high, although with notable variation. For some respondents, cost is a primary barrier because passive measures require upfront investment with uncertain short-term returns. For others, including H and C, clinical safety, healing environment quality and demonstrable performance are more decisive. Cost should therefore be understood not as a standalone barrier, but as something shaped by uncertainty, ownership and the ability to demonstrate long-term value. Timing was ranked lower by several respondents, partly because hospital projects are typically developed by integrated design teams from an early stage.

The low average ranking of law and regulation is notable. Formal building regulations were not perceived as the main obstacle to passive cooling. However, this does not imply that regulatory constraints are irrelevant. The interviews suggest that clinical requirements, internal risk protocols and infection-prevention standards are more decisive than general building legislation. This explains why regulation can rank low while clinical control remains a dominant implementation barrier.

5.3.2 Indicative prioritisation of drivers and stakeholder variability

The driver ranking shows that ambition is the strongest driver on average and showed relatively high agreement across respondents. This aligns with the qualitative finding in section 5.2 suggesting that passive cooling does not emerge automatically from sustainability awareness or technical optimisation. It needs to be formulated as an explicit project ambition early in the process, before the PvE, climate concept and cost framework start narrowing the design space.

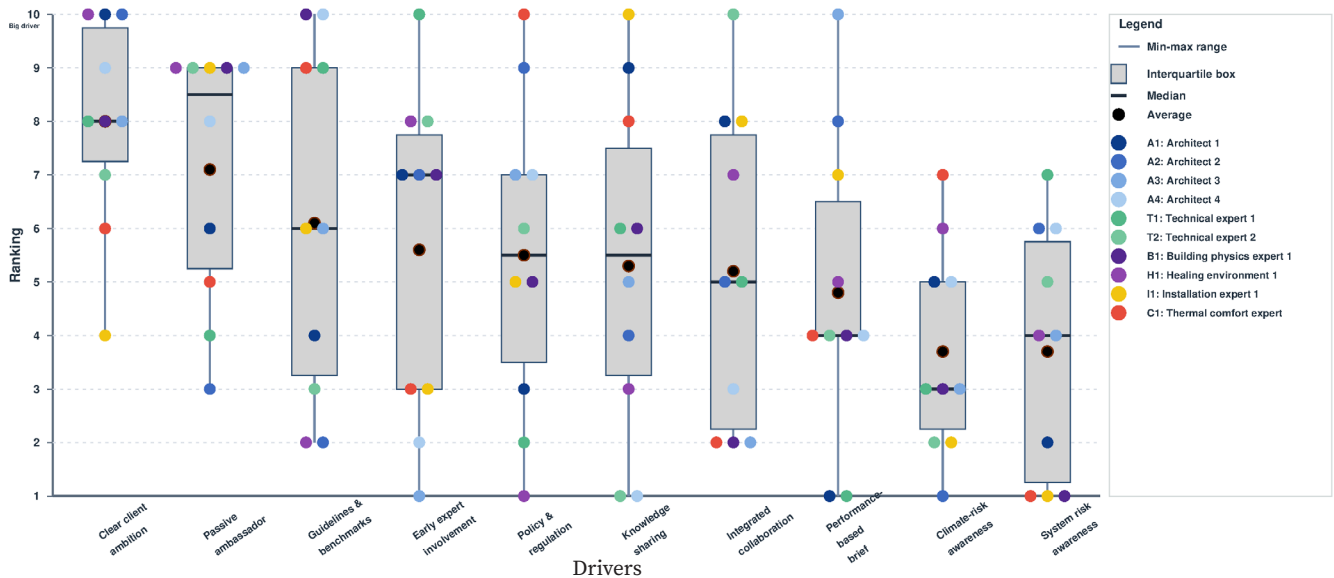


Fig. 5.4: Box plot showing the relative ranking of implementation drivers.

Ambassadorship, benchmarks and expertise also ranked relatively high, but with considerable variation across respondents. This supports the qualitative finding that passive cooling requires clear ownership and interdisciplinary coordination. The variation indicates that stakeholders assign implementation responsibility differently: some emphasise client or architectural leadership, while others prioritise technical expertise or cross-disciplinary collaboration.

Experts, regulation, knowledge, and PvE requirements show a wider spread. Their perceived relevance depends strongly on stakeholder background. For some respondents, formal or PvE requirements, are essential to make passive strategies defensible; for others, ambition, cooperation and ownership are more decisive. This indicates that evidence alone is insufficient unless it is embedded in a decision-making process capable of acting on it.

Awareness ranked relatively low. This is remarkable because overheating, installation dependency and climate risk are common arguments for passive design. The ranking suggests that awareness of these risks does not automatically translate into implementation.

As an exploratory check, Spearman rank correlations were calculated between ranked barriers and drivers (Appendix S). The average barrier–driver correlation was approximately zero, indicating that barriers and drivers are not direct opposites. Implementation barriers can therefore not be addressed simply by strengthening the corresponding driver category.

Some correlations are conceptually plausible, such as the relation between timing as a barrier and early expert involvement as a driver, which underlines the importance of introducing technical knowledge before key requirements are fixed. Other correlations are less robust and should be interpreted cautiously.

5. IMPLEMENTATION BARRIERS & DRIVERS - RESULTS

The respondent-similarity analysis in Fig. 5.5 shows limited overall agreement in the ranking of barriers and drivers. Average similarity within the architect group is close to zero for barriers (-0.01), drivers (0.06) and combined rankings (0.02), indicating that stakeholder role alone does not explain prioritisation patterns. This suggests that individual project experience, disciplinary focus and interpretation of the ranking cards influenced responses more strongly than professional category.

Some respondent pairs show moderate similarity, particularly B1-A4 (0.56), H1-A1 (0.55), T1-B1 (0.45) and A2-T2 (0.44). These similarities indicate partial alignment between specific respondents, but not a consistent cluster across stakeholder groups. Conversely, negative correlations, such as A2-B1 (-0.30), A3-T1 (-0.28) and C2-T2 (-0.27) show that some respondents ranked barriers and drivers in substantially different orders.

Overall, the heatmaps confirm that implementation priorities are heterogeneous rather than role-determined. The ranking exercise should therefore be interpreted as exploratory evidence of divergent stakeholder perspectives, while the qualitative interview data remain essential for explaining why certain barriers and drivers were prioritised.

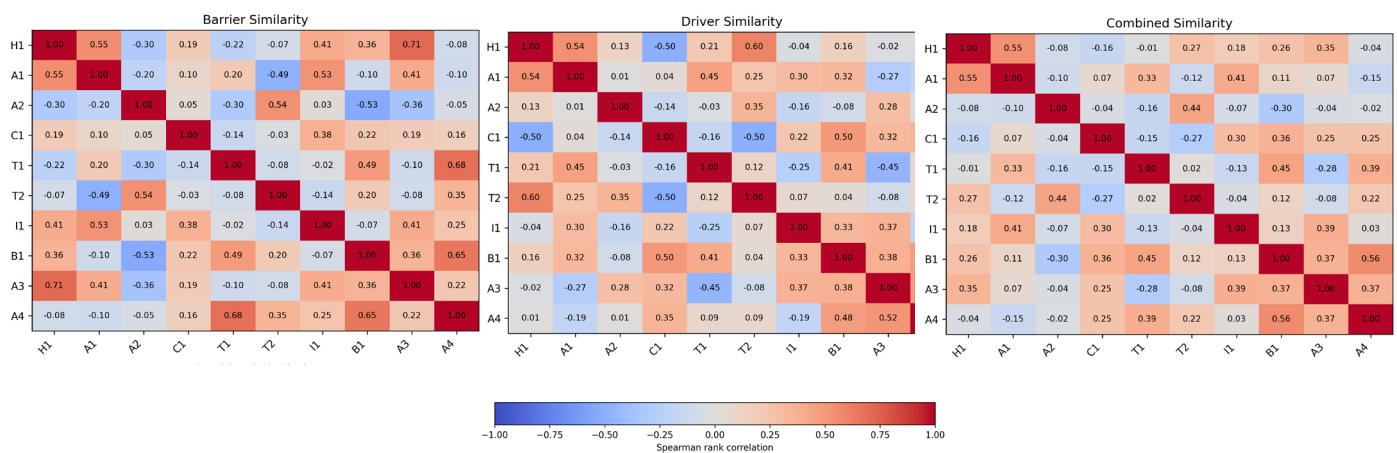


Fig. 5.5: Spearman rank correlation between participating stakeholders in the interview.

5.4 Design and process recommendations

5.4.1 P-ladder

The interview findings identified multiple barriers and drivers for implementing passive cooling in healthcare design. Since many of these issues reflect broader process conditions, they were clustered into six recurring categories: Purpose, Price, People, Process, Program and Proof.

This clustering translates separate interview findings into an actionable framework. Rather than addressing each barrier individually, the P-ladder defines the conditions needed to make passive-first design feasible in practice. As shown in Table 5.1, each P-condition links specific barriers to corresponding drivers. The P-ladder therefore connects the interview analysis to the recommendations by showing both what limits passive cooling and which conditions can support its implementation. The complete P-ladder is shown on the next page.

6P condition	Mitigating barriers	Enabling drivers
Purpose	Unclear ownership and responsibility: it is unclear who owns passive concepts and who remains responsible for them. Limited stakeholder conviction or interest: passive cooling lacks sufficient support from key stakeholders.	Clear client ambition: strong sustainability goals legitimise passive-first design. Internal champions: dedicated actors keep passive strategies active. Climate-risk awareness: future heat risk supports alternative design choices.
Price	Short-term cost logic: passive measures are disadvantaged when only initial investment is considered. Cost perception: passive cooling is perceived as more expensive than conventional systems..	Life-cycle valuation: energy, maintenance, comfort and reduced system dependency are included in decisions. Failure-risk costing: installation risks and failure costs are made explicit.
People	Knowledge gaps: passive cooling expertise is unevenly distributed. Late expert involvement: relevant expertise enters after key design freedom is lost. Fragmented collaboration: stakeholders work from separate scopes rather than a shared climate concept.	Early expert involvement: building physics and comfort expertise define ambitions and criteria early. Knowledge sharing: shared understanding increases support. Integrated collaboration: disciplines align around one climate strategy from the start.
Process	Timing in the design process: passive expertise is often involved too late. System inertia: the design process follows familiar routines, making change difficult. Conventional installation-led workflow: mechanical capacity becomes the default starting point.	Early decision structure: passive options are assessed before key design choices are fixed. Flexible process: design teams can question routines and compare climate concepts. Integrated working agreements: procedures define how climate decisions are made.
Program	Closed PvE: mechanical cooling assumptions restrict solution freedom. System-driven requirements: comfort is translated into technical system demands rather than user performance. Regulatory caution: rules are interpreted as constraints on passive cooling.	Performance-based PvE: comfort and cooling requirements are formulated as outcomes. ambitions, design principles, performance criteria, technical demands and wishes are separated. Policy as support: regulation or internal policy is aligned with passive-first objectives.
Proof	Limited evidence: guidelines, benchmarks and validated examples are insufficient. Control uncertainty: mechanical systems are perceived as more predictable. Context dependency: performance varies with typology, climate, loads, users and system interaction.	Performance benchmarks: practical guidelines provide reference values. Scenario-based evidence: simulations and risk ranges make performance credible. Decision-ready proof: results are translated into comfort, cooling load, energy, cost, risk and operation.

Table 5.1: Translating barriers and drivers into 6 P conditions

Because the early design phase plays a decisive role in defining the project ambition and establishing a passive-first design vision, it is important that stakeholders develop a shared knowledge base and consider passive design choices from an integrated perspective. To support this process, a set of Dialogue Starter Cards was developed as an additional tool alongside the P-ladder. The cards are intended to facilitate structured discussion during the initiation phase. They help design teams explore the potential of passive strategies, clarify ambitions, and translate these ambitions into related design requirements. Figure 5.6 shows an example of one of the cards. The complete card set, tailored to the different stakeholders involved in the design process, is provided in Appendix T.

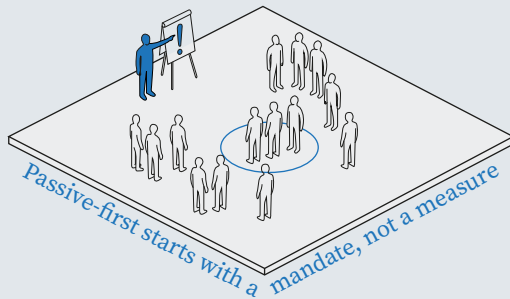
STAKEHOLDER ARCHITECT	CARD 04	STAKEHOLDER USER / HEALING ENVIRONMENT	CARD 05	STAKEHOLDER COST EXPERT	CARD 06	STAKEHOLDER CLIENT	CARD 13
CAN AIR MOVEMENT BE ACTIVELY USED AS A STRATEGY TO IMPROVE COMFORT IN PATIENT ROOMS? Fact Increasing air velocity enhances heat loss from the human body, allowing higher indoor temperatures while maintaining comfort. Design implications e.g. - Integration of ceiling fans - Increased ceiling height - Air supply near patient zone Programme implications - Define acceptable air velocity - Allow local control systems - Include adaptive comfort criteria		TO WHAT EXTENT SHOULD PATIENTS OR STAFF BE ABLE TO INFLUENCE THEIR LOCAL INDOOR CLIMATE? Fact Perceived control over the indoor environment significantly improves thermal satisfaction, even when physical conditions remain unchanged. In addition, enabling adaptive actions (e.g. adjusting airflow, temp. or shading) allows occupants to tolerate a wider temperature range. Design implications - Integrate operable elements (windows, shading devices) - Allow local air movement (e.g. fans, directional airflow) - Design zones with different thermal conditions - Position controls within reach of users or staff Programme implications - Define levels of user control - Include adaptive comfort criteria - Specify provisions for local environmental adjustment - Align control strategies with infection control and safety requirements		SHOULD PASSIVE CLIMATE STRATEGIES BE EVALUATED AS ARCHITECTURAL COSTS, ENGINEERING COSTS, OR LONG-TERM OPERATIONAL INVESTMENTS? Fact Passive strategies are often overlooked because their costs appear early in the project, while many of their benefits emerge later through reduced installation size, lower operational energy use and improved thermal resilience. Programme implications - Reserve budget for early climate simulations and passive studies - Include lifecycle performance alongside initial investment costs - Allow budget transfer between architectural and installation scopes		WHO IS RESPONSIBLE FOR PROTECTING PASSIVE AMBITIONS DURING BUDGET OR PLANNING PRESSURE? Fact Passive ambitions often disappear when no stakeholder carries responsibility. Programme implications - Assign responsibility for passive performance decisions - Review passive ambitions at every decision gate - Establish shared performance priorities early in the project	
PASSIVE DESIGN DIALOGUE CARDS		PASSIVE DESIGN DIALOGUE CARDS		PASSIVE DESIGN DIALOGUE CARDS		PASSIVE DESIGN DIALOGUE CARDS	

Fig. 5.6: Cards from the passive-first dialogue starter card set, full set is provided in Appendix T. (Author's work)

P-ladder: Enabling Passive-First Design philosophy

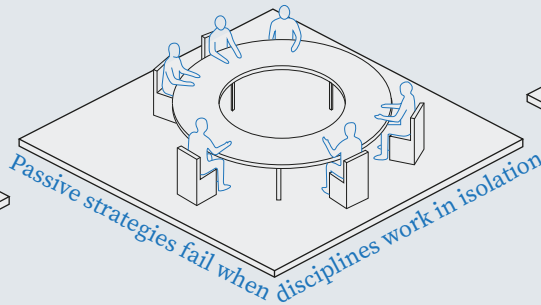
This framework is intended for clients, architects, consultants, and other stakeholders involved in the early design of healthcare buildings. It translates the main findings of "Passive-first healthcare design" into a practical reference sheet that can be used during project initiation, briefing, and early design discussions. The poster helps teams identify the conditions need to be in place to enable passive-first design, when key decisions should be made, and where barriers are likely to arise. It is designed to support dialogue, stimulate decision-making, and make passive cooling strategies more actionable within practice. The framework is part of thesis research on the integration of passive cooling in healthcare design and is grounded in findings mainly from interviews and a case study simulation.

What conditions build persuasion?



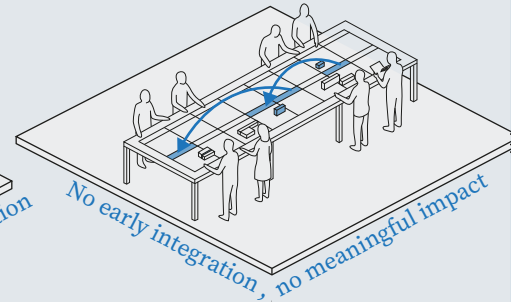
Purpose

Passive strategies only become viable when they are defined as **project ambitions** from the start. This requires a client-side mandate, **explicit ownership**, and a clear position that user-oriented comfort is part of the design brief, not an optional add-on.



People

Passive-first design requires a **shared knowledge base** between client, architect, building physics, building services, users, and contractors. The aim is not only early involvement, but **equal understanding** of what passive design can and cannot do.



Process

Passive-first design must be allowed to influence form, orientation, façade, zoning, and layout before these decisions become fixed. This requires **flexibility in the process** and a **willingness to question standard routines** when they limit passive potential.

When to decide what?

Initiation

Explore alternatives before locking in the design direction

- **01 — Passive ambition**
Is passive-first an explicit project ambition, or only a sustainability preference?
- **02 — Ownership**
Who owns the passive ambition and has the mandate to defend it when cost, risk, or planning pressure increases?
- **03 — Divergent exploration**
Has the team explored multiple climate concepts before choosing one design direction?
- **04 — Design freedom scan**
How much is already fixed by the urban plan: orientation, building depth, height, massing, façade exposure, and spatial layout?
- **05 — Value logic**
Will passive strategies be judged only on CAPEX, or also on TCO, comfort, resilience, operational costs, and reduced system dependency?
- **06 — Early budget**
Is there a dedicated budget for passive optimisation, simulations, façade studies, and stakeholder workshops?

Passive ambition note + design freedom scan

Programme/PvE

Define ambition before technical solutions.

- **01 — Layered performance brief**
Is the brief structured from ambition and design philosophy to performance criteria before fixed technical solutions are prescribed?
- **02 — Comfort philosophy**
Is comfort defined only by temperature setpoints, or through a broader framework including air speed, radiant conditions, exposure time, adaptability, and local control?
- **03 — Requirement conflicts**
Have overlapping or conflicting requirements been reviewed by building physics and technical advisors?
- **04 — Room-type differentiation**
Are ambitions and requirements differentiated by room type instead of defined for the hospital as one uniform building?
- **05 — Passive applicability matrix**
Has the team identified where passive, hybrid, or active-first strategies are appropriate?
- **06 — Infection prevention boundaries**
Under which conditions may natural ventilation, openable windows, lower airflow, or local air movement be acceptable?
- **07 — Uncertainty position**
How will the project deal with uncertainty: fixed values only, or acceptable performance ranges and scenarios?

Layered PvE + comfort framework + room-type matrix

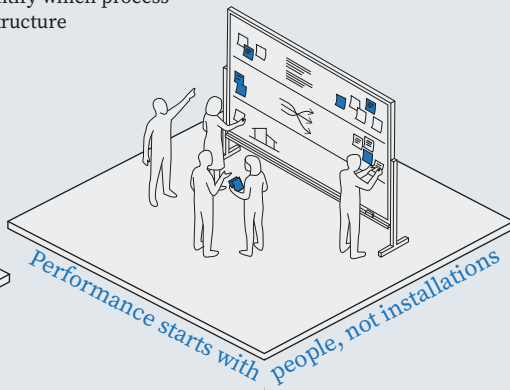
Schematic design/

Test passive potential before fixed

- **01 — Team readiness**
Have all relevant stakeholders shared a shared baseline understanding of passive potential? Are spatial decisions fixed?
- **02 — Scenario workshop**
Has the team compared at least one passive scenario with conventional mechanical, hybrid, or active systems? Are passive with active fallback?
- **03 — Passive-first sequencing**
Has the project first tested heat gains, orientation, façade, shading, massing, and movement before sizing active systems?
- **04 — Façade as first line of defense**
Are solar gains reduced through orientation, g-value, visible light transmission, and maintenance?
- **05 — Internal load realism**
Are internal heat loads modeled for different patient rooms with different equipment?
- **06 — User-centred comfort**
Is the design testing comfort at different exposure durations and radiant effects?
- **07 — Spatial flexibility tenets**
Has the team discussed where passive is necessary and where differentiation is needed?

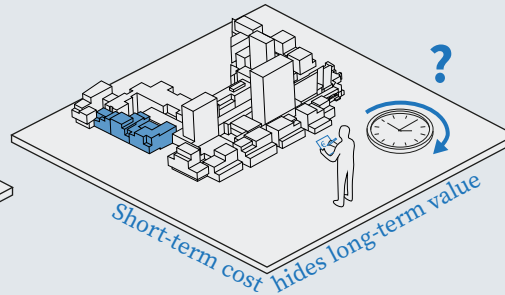
Scenario comparison +

the thesis "Towards
ntify which process
ructure



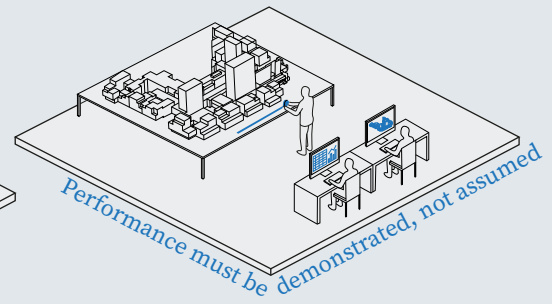
Programme

A passive-first brief should distinguish between **ambition, performance criteria, technical requirements, and wishes**. Comfort must be defined through **user-oriented performance**, including temperature, air movement, radiant conditions, adaptability, exposure time, and local control, rather than fixed system solutions.



Price

Passive strategies often require early design effort or upfront investment, while their **value appears over time** through lower energy demand, reduced system dependency, operational resilience, and longer lifespan. They must therefore be **assessed beyond CAPEX**.



Proof

Passive-first design depends on context: building type, internal loads, user behaviour, climate, and spatial-technical integration all affect outcomes. Conviction is built by showing **performance ranges, uncertainties, and scenario results** instead of single-value promises.

SO

orm is fixed.

been involved early and brought to a
of passive cooling before core

three climate scenarios:

id passive-active, and maximum

ce
reduction through form,
ass, ventilation, and local air
systems?

f defence

n orientation-specific façade design,
on, external shading, view quality,

n
ed per room type, especially for
equipment densities?

t
user level, including air movement,
on, and local control?

sion

generic hospital flexibility is
ated passive strategies are justified?

passive concept strategy

Concept design/VO

Prove performance before final choices.

- **01 — Quantified performance ranges**
Are passive strategies quantified in terms of cooling load, overheating risk, comfort, energy, costs, and system dependency, and are results expressed as performance ranges?
- **02 — Scenario-based validation**
Are best-case, worst-case, future climate, heatwave, user variation, and internal load scenarios calculated?
- **03 — Active fallback definition**
For each room category, what is the passive base strategy and when does active cooling take over?
- **04 — Openable windows strategy**
If windows are included, are opening limits, window contacts, control logic, acoustic constraints, outdoor air quality, and system interaction defined?
- **05 — Air movement and infection risk**
Are local fans, bed-level airflow, natural ventilation, and HEPA concepts assessed together with air quality, contaminant transport, draught risk, and controllability?
- **06 — TCO decision**
Are higher early investments compared with reductions in cooling capacity, energy use, maintenance, replacement costs, and extended lifespan?
- **07 — Passive cooling decision gate**
For each passive strategy, is it continued, modified, or rejected, and is the reason documented?

Passive decision gate + scenario evidence + TCO comparison

Final design/DO

Integrate and protect the passive strategy.

- **01 — Strategy protection**
Which passive strategies from the programme and VO decision gate are still included, and which have changed?
- **02 — Passive-active integration**
Do passive and mechanical systems support each other, or do they conflict?
- **03 — Control logic**
Are window opening, shading, cooling, ventilation, user control, and set-back modes coordinated in one control strategy?
- **04 — Modularity**
Are installations modular, zoneable, and responsive to differentiated room loads and façade performance?
- **05 — User control detailing**
Which controls are available per user group, and are they safe, understandable, bounded, and maintainable?
- **06 — Monitoring protocol**
Is post-occupancy monitoring specified for temperature, humidity, air speed, shading use, window use, complaints, user control, energy, and perceived comfort?
- **07 — Evidence feedback loop**
How will measured performance feed back into future PvEs and design standards?

Coordination check + control strategy + monitoring protocol

5.4.2 Design exploration 2050 patient room

To explore the applicability of natural ventilation and local air movement as a thermal comfort strategy in healthcare environments, a focus group workshop was organised with building physics experts. The objective of the workshop was to systematically explore the design possibilities for increasing air speed at patient-room level through passive design interventions, while simultaneously reducing the design space to a limited number of feasible and research-relevant concepts for further design exploration.

The workshop followed a structured divergence-convergence approach. In the first phase, participants identified and discussed physical parameters and airflow mechanisms that could influence local air speed and thermal comfort in patient rooms. This enabled a broad exploration of the potential design space surrounding wind-driven ventilation, buoyancy-driven flow, geometric acceleration, and façade-related interventions. In the second phase, these parameters were clustered, combined, and critically evaluated against healthcare-related constraints such as draught risk, infection prevention, controllability, and implementation feasibility.

This process resulted in a controlled reduction of the design space and the definition of four preliminary design principles. In addition to identifying technically feasible concepts, the workshop deliberately stimulated out-of-the-box thinking in order to move beyond conventional natural ventilation approaches commonly applied in healthcare buildings.

The simulation and interview results show that passive ventilation is constrained by limited wind availability, uncertain airflow behaviour, clinical requirements and the need for operational control. Natural ventilation provides useful occupant-level cooling only during a limited number of hours, while stakeholders identify unpredictability, infection control and controllability as key implementation barriers. The following design explorations therefore examine how outdoor air could be supplied more stably and predictably to the patient room. Rather than proposing standard solutions for current practice, they explore passive-first concepts for 2050 that aim to increase usable hours of elevated air speed, reduce airflow uncertainty and align ventilation strategies with patient comfort, staff comfort and clinical constraints. First, design objectives are shown (Fig. 5.8), followed by four concept directions (Fig. 5.9 - 5.12), and finally a futuristic 2050 passive patient room (Fig. 5.13).

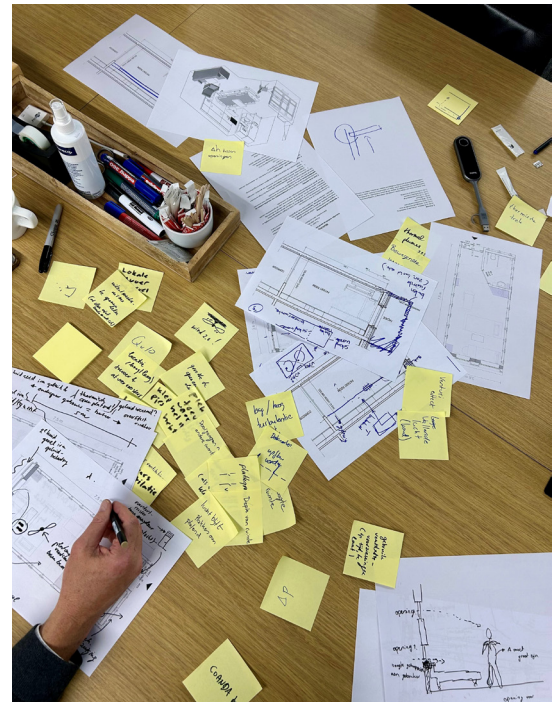
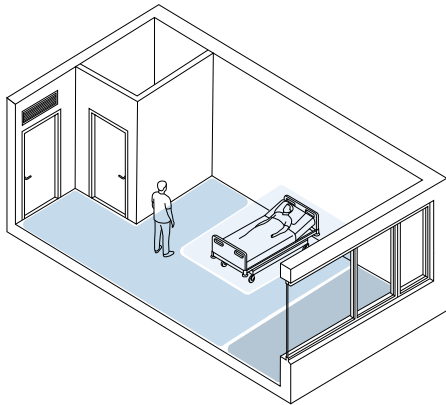


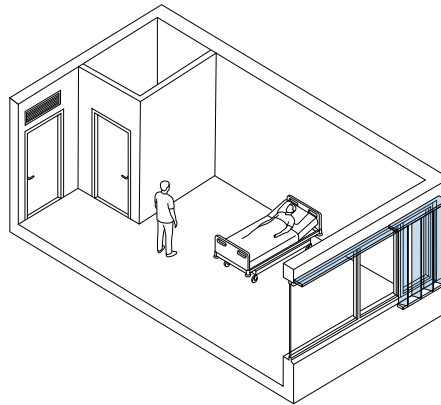
Fig. 5.7: Focus group workshop on passive natural ventilation in patient rooms.

5. IMPLEMENTATION BARRIERS & DRIVERS - RESULTS

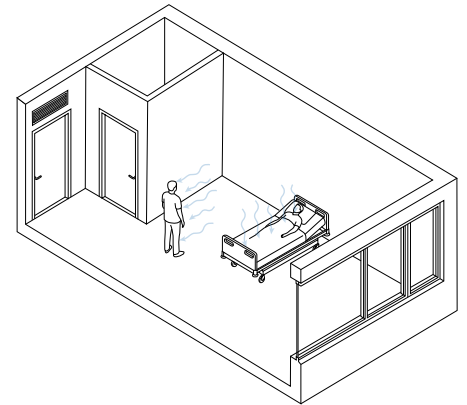
Design exploration objectives



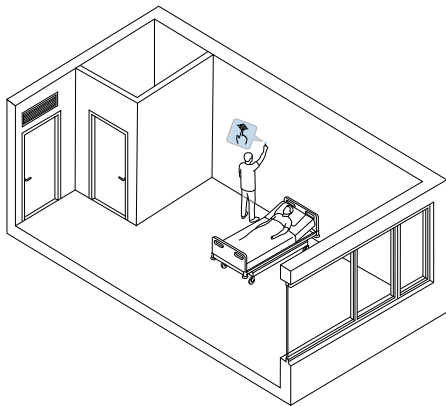
Differentiate thermal conditions within the patient room according to user position, activity level and vulnerability.



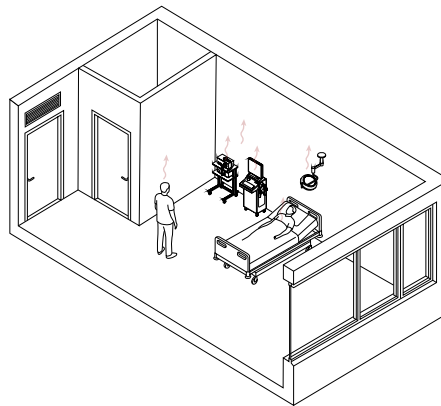
Prevent direct solar exposure in the bed zone and minimise spatially non-uniform solar patches.



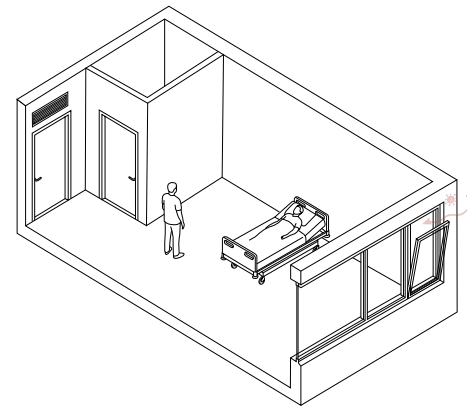
Provide stable and evenly distributed occupant-level air movement to reduce thermal asymmetry and draught risk.



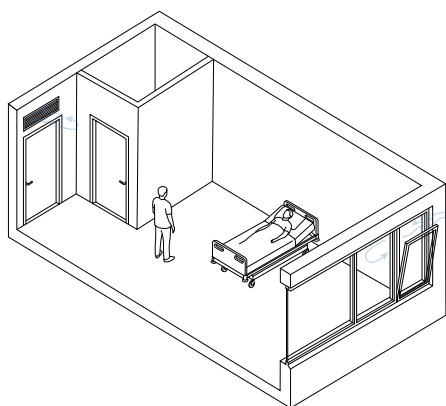
Enable appropriate user or staff control over local thermal conditions without compromising clinical safety.



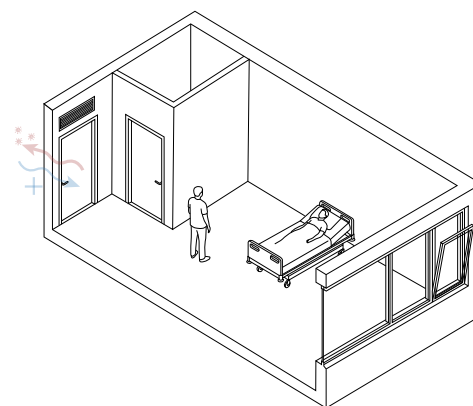
Discharge accumulated heat through high-level exhaust paths before thermal build-up affects occupied zones.



Limit ingress of outdoor noise, particulate matter and pollutants while maintaining ventilation potential.



Prevent short-circuiting between inlet and outlet openings to maintain effective room-level heat removal.



Maintain predictable airflow direction and pressure relationships to support infection-control requirements.

Fig. 5.8: Summary of design objectives. (Author's work)

Design explorations for occupant-level airflow

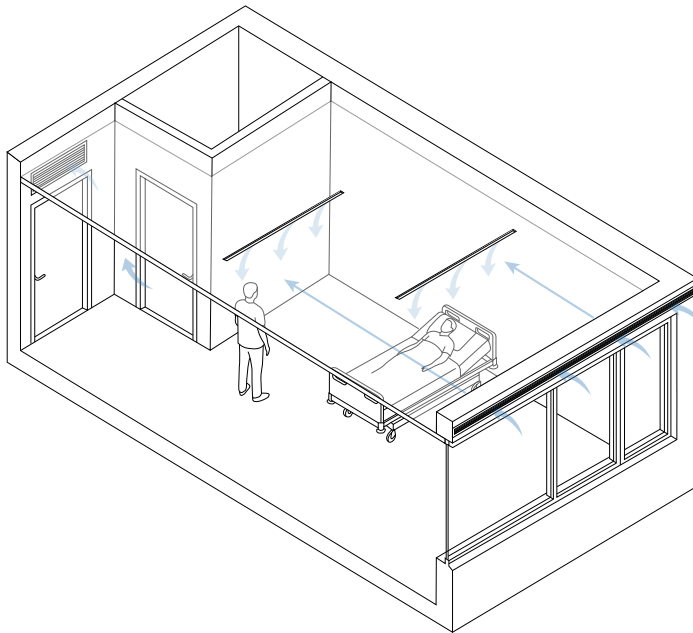


Fig. 5.9: Design exploration: Ceiling-integrated air distribution

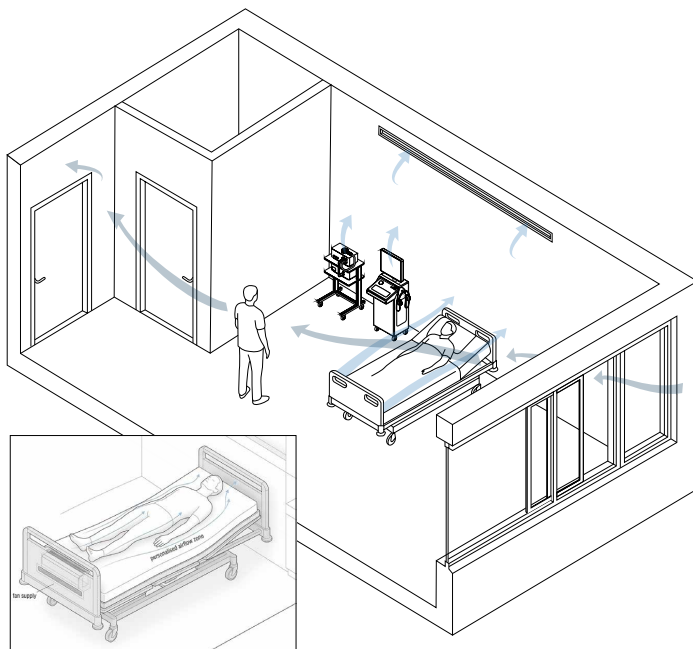


Fig. 5.10: Design exploration: Bed-integrated microclimate and separate airflow zones

1. Ceiling-integrated air distribution

This option introduces outdoor air through a continuous narrow slot at the top of the façade and distributes it through the ceiling void towards controlled supply points. The strategy allows outdoor air to penetrate deeper into the room, provided that inlet pressure is sufficient, internal resistance is limited and outlet positions prevent short-circuiting or recirculation. Supply openings must be designed to avoid cold downdraught and unintended heat gain from ceiling-integrated fixtures. In winter, the inlet can be closed to prevent draught, while the façade grille and suspended ceiling require accessible maintenance zones.

2. Bed-integrated microclimate and separated airflow zones

This option integrates two local fans into the bed headwall to create directed airflow around the patient zone. Airflow direction and speed can be adjusted by the patient, enabling individual control over local thermal conditions. For staff cooling, high-level windows or grilles supply upward-directed airflow above the bed towards the staff zone, with high-level exhaust on the opposite wall. The separation between patient and staff airflow paths requires further assessment to prevent premature mixing, while acoustic performance, outdoor particulate ingress and clinical acceptability remain critical design constraints.

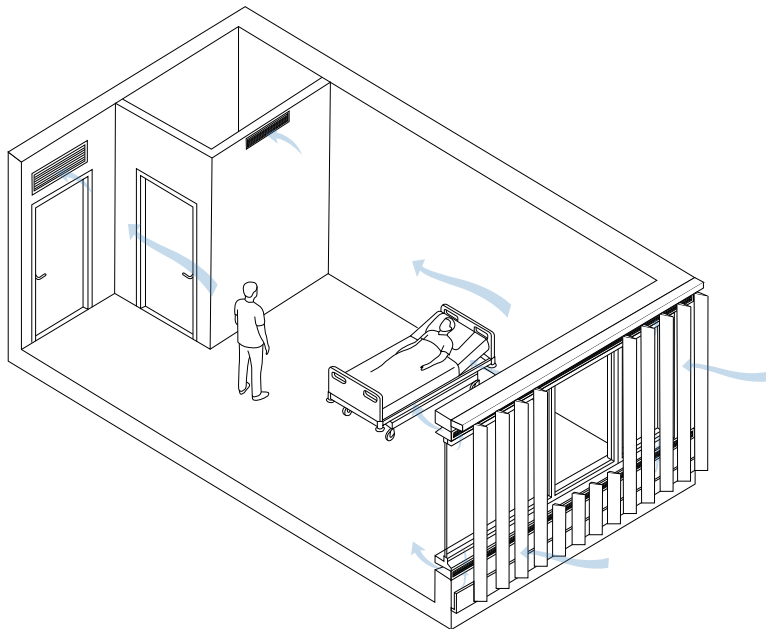


Fig. 5.11: Design exploration: Aerodynamic solar shading and Coandă-based airflow guidance

3. Aerodynamic solar shading and Coandă-based airflow guidance

This variant combines external solar shading with aerodynamic façade panels that guide wind-driven airflow towards controlled inlet openings. Wing-shaped vertical elements modify local pressure distribution and promote flow attachment along the façade, potentially improving air capture at selected openings. High-level acoustically treated and filtered grilles supply air to the staff zone, while lower protected openings near the bed create a more sheltered patient airflow path. Panel geometry, spacing and orientation require optimisation to avoid flow separation, turbulence and short-circuiting, while internal airflow paths must preserve momentum towards the intended occupied zones.

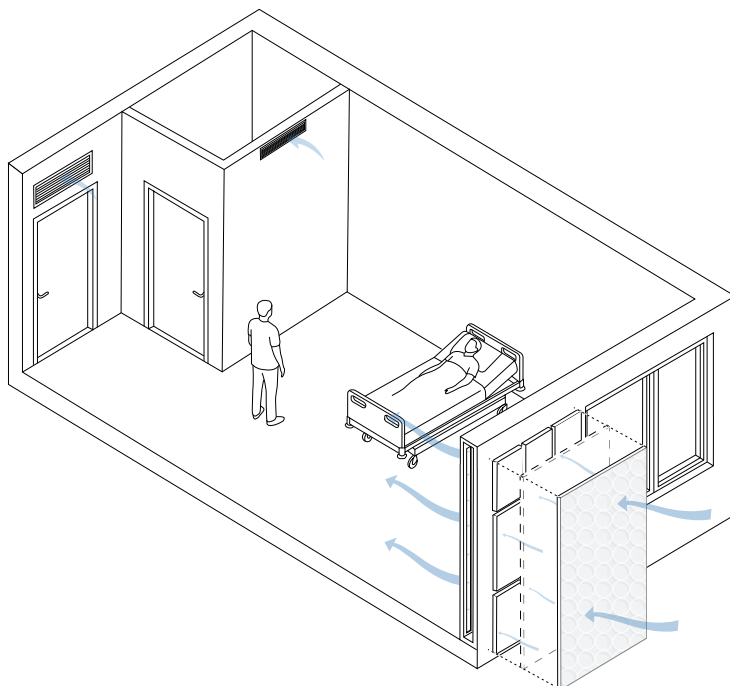


Fig. 5.12: Pressure-buffer façade with distributed air intake

4. Pressure-buffer façade with distributed air intake

This option keeps conventional windows closed during normal operation and introduces outdoor air through a perforated external façade layer. The air is collected in a ventilated cavity that acts as a pressure-stabilising buffer before entering the room through controllable vertical slots. Adjustable slot orientation allows local airflow direction to be tuned by users or staff. By distributing air intake across the façade, the strategy aims to create more stable and draught-reduced ventilation than conventional operable windows. During winter, supply openings can be closed to maintain airtightness and prevent unwanted cold infiltration.

Futuristic passive-cooled patient room

This design exploration should not be read as an optimised or final patient-room proposal. The performance of passive and hybrid cooling strategies is highly context-dependent and would vary with orientation, façade exposure, internal heat loads, clinical requirements, outdoor air quality, pressure regimes and operational control. The drawing therefore serves as a spatial exploration of how different strategies could be combined within a future 2050 patient-room concept, rather than as a validated design solution.

The exploration combines the design ideas introduced in Figures 5.9–5.12 and translates several principles discussed in this thesis into one speculative patient-room concept, including solar-gain reduction, pressure-buffered façade design, controlled airflow paths, local patient-level air movement, high-level exhaust, thermal buffering and ground-coupled cooling. Its purpose is not to present a final technical solution, but to challenge installation-led thinking and visualise how passive-first principles, airflow control, user differentiation and clinical constraints could be discussed at an early design stage. This does not imply that the technical, clinical or organisational barriers identified in the previous chapter are solved by the design. Further development would require detailed simulation, airflow modelling, infection-control assessment, acoustic and cost evaluation, user testing and integration with actual hospital design protocols.

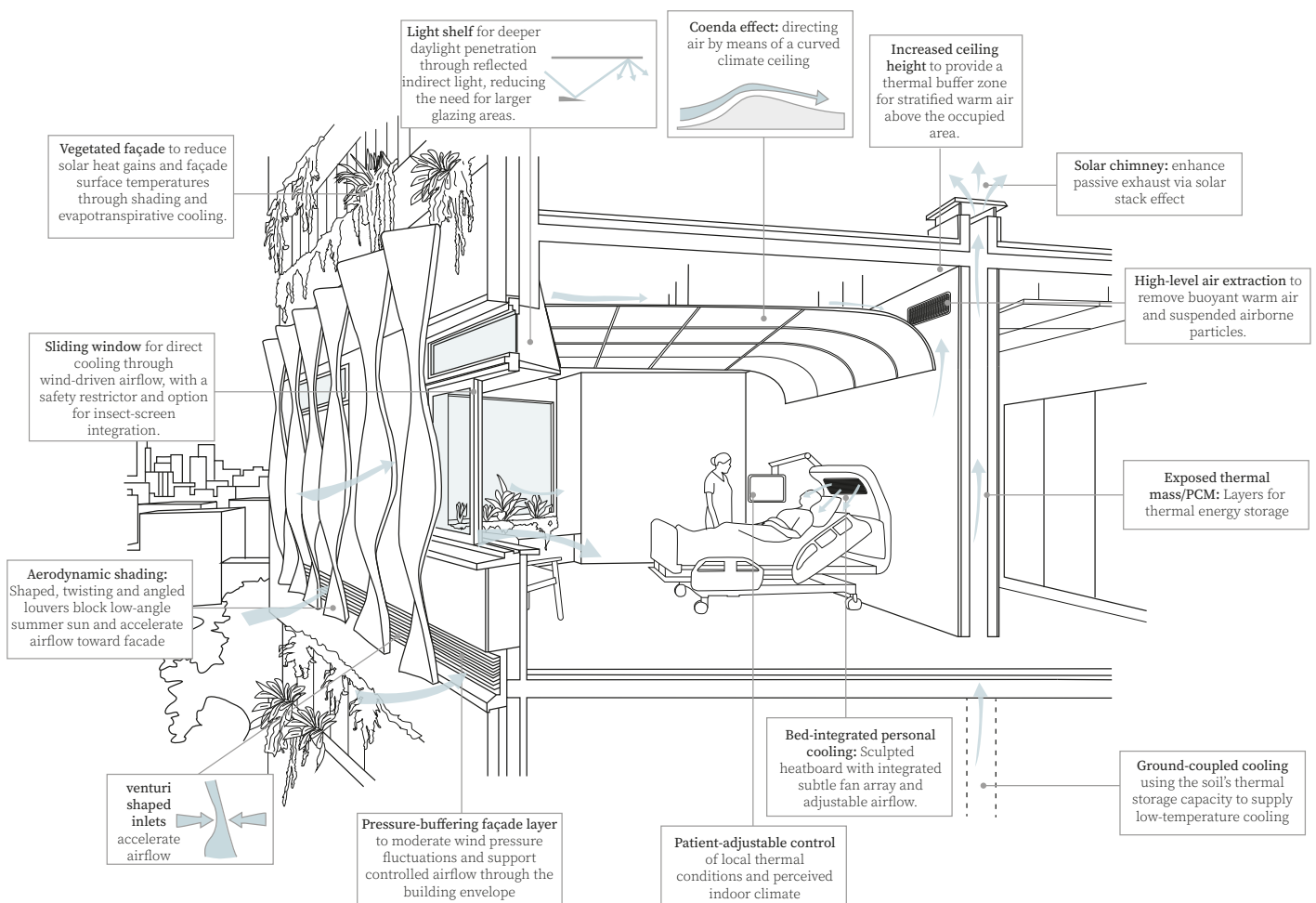


Fig. 5.13: Design exploration of passive-first and hybrid cooling strategies at patient-room scale. (Author's work)

5.5 Stakeholder interview discussion and limitations

The interview study included stakeholders from different roles within healthcare projects to capture multiple perspectives on passive and hybrid cooling implementation. This strengthens the qualitative depth of the findings, but limits comparability between respondents. Differences in professional background, terminology and project role influenced how participants interpreted barriers, drivers and responsibilities. The ranking results should therefore be read as indicative patterns rather than statistically robust evidence. The main limitation is the uneven sample composition. Some stakeholder groups were represented by only one respondent, which risks generalising individual views to a wider professional group. A larger and more balanced sample would be needed to strengthen external validity, particularly for stakeholder-specific conclusions.

The card-ranking exercise also introduces uncertainty. Although explanatory notes were provided and participants were asked to think aloud, interpretation bias could not be fully avoided. The predefined cards may also have missed relevant implementation factors, despite the option to add items. In addition, the ordinal ranking shows order but not relative weight, while several participants indicated that some differences were larger than the ranking could express. Pairwise comparison or weighted scoring could provide a more precise representation of stakeholder priorities. Since several respondents were involved in the case study, response bias may also have affected the degree of criticism expressed.

5.6 Sub-conclusion implementation barriers and drivers

How can simulation-based performance evidence and stakeholder-based implementation findings inform early-stage design guidance for occupant-centred, function-specific passive-first cooling strategies in healthcare buildings?

Despite the indicative nature of the interview findings, the combined simulation and stakeholder results show that passive-first cooling in healthcare is not constrained by technical feasibility alone. Simulations identify where passive and hybrid strategies are physically effective, such as solar heat-gain reduction, local air movement and cooling setpoint flexibility. The interviews show why these strategies often fail to become decisive in practice: fragmented PvE requirements, late involvement of expertise, unclear ownership, short-term cost logic, clinical risk perception and an installation-led design culture all reduce their influence during early decision-making.

This means that passive strategies need more than isolated technical measures or generic sustainability ambitions. They require an enabling project structure in which comfort ambitions, user profiles, clinical risk categories and ownership are defined per healthcare function before key spatial and technical decisions are fixed. Simulation outputs should therefore be translated into decision-relevant indicators, including comfort robustness, cooling-load reduction, user-specific thermal risk, airflow controllability, spatial impact, operational reliability and long-term value.

Early-stage guidance should follow a sequential logic. Firstly, the design team should define the comfort ambition, risk profile and responsible actor for each healthcare function. Secondly, passive potential should be tested under current and future climate conditions using internal heat-load assumptions and occupant-centred indicators such as SET. Thirdly, the results should be evaluated against implementation conditions such as infection-control boundaries, user control, maintenance, flexibility and stakeholder responsibility. Only then should active systems be dimensioned as hybrid fallback for the remaining demand, rather than as the default starting point.

Overall, occupant-centred passive-first cooling requires quantified performance evidence, clear project ambition, early interdisciplinary cooperation and accountable ownership from the earliest design stages. These conditions are needed to prevent passive strategies from becoming secondary additions once mechanical systems have already defined the design direction.

6

DISCUSSION, CONCLUSION AND REFLECTION

This chapter synthesises the main findings of the research and answers the research questions. It discusses the implications of passive and hybrid cooling strategies for occupant-centred thermal comfort, cooling demand and early-stage healthcare design. The chapter also reflects on the methodological limitations, the transferability of the findings and the broader relevance of a passive-first design approach for future hospital patient rooms.

6.1 Cross-chapter discussion

6.1.1 Validation and consistency with previous research

Solar control: strong physical effect, limited comfort effect

The results are broadly consistent with previous passive-cooling research, but also show that reported performance cannot be transferred directly to hospital patient rooms. The passive-envelope scenario confirms the effectiveness of façade-based solar control: transmitted solar radiation decreases from 11.97 to 2.38 kWh/m², corresponding to an 80.1% reduction. This aligns with Prieto Hoces et al. (2018), who report substantial peak cooling-load reductions from external shading in mid-latitude climates. However, the comparison is not one-to-one: Prieto Hoces et al. report peak cooling-load reduction, whereas this study reports transmitted solar radiation reduction. The distinction is important, because the reduced solar load does not translate into proportional thermal comfort improvement. Average T_o decreases from approximately 42.9°C in the free-floating case to 38.9°C in the passive-envelope case, but remains far above acceptable comfort levels (Fig. 4.9). The passive envelope therefore performs as a heat-gain prevention measure, not as a stand-alone overheating solution.

Why literature reports stronger comfort effects

This also explains why some literature reports stronger passive-cooling effects. Studies by Raji et al. (2017, 2019) often assess combined packages of glazing optimisation, solar shading, natural ventilation, night flushing and thermal mass. Moreover, these studies frequently concern office-like or high-rise contexts with less continuous occupancy, healthier users and greater adaptive potential. A hospital patient room differs substantially: it is continuously occupied, contains vulnerable users, has strict comfort and hygiene expectations, and includes persistent equipment loads. The present results therefore support the literature, but refine its applicability: passive-cooling benchmarks must be reinterpreted for healthcare spaces with high internal gains and limited adaptive capacity.

Internal gains as the dominant residual load

The simulations further confirm that passive cooling performance depends on the full heat balance, not façade design alone. After solar transmission is reduced, internal gains become dominant. In the free-floating case, lighting and equipment contribute 13.7 kWh/m², exceeding the remaining transmitted solar gains in the passive-envelope scenario. The sensitivity analysis strengthens this finding: a 50% reduction in equipment power lowers average T_o by approximately 3.2°C, whereas reduced occupancy and timber construction have much smaller effects (Fig. 4.10). For patient rooms, internal heat-load management should therefore be considered part of passive design, rather than a separate operational issue.

Natural ventilation and cooling demand: context-dependent comparison

The natural-ventilation and hybrid results are also consistent with the context-dependent performance reported in the literature. Zhang et al. (2019) report cooling energy reductions of up to 40% from natural ventilation and approximately 25% from fixed shading. The larger ideal cooling-load reduction in this study should not be interpreted as a direct improvement over those values, because it results from a hybrid strategy: local air movement enables a cooling setpoint increase from 24°C to 26°C (section 4.2.5). In addition, the reported reduction concerns ideal cooling load, not final electricity use or full HVAC performance. The result therefore demonstrates the value of air-speed-driven setpoint flexibility, but its magnitude remains dependent on modelling assumptions, COP, fan control and omitted system dynamics.

Why active systems remain necessary

The findings also support the argument by Lu et al. (2016) that active systems remain attractive because they compensate for uncertainty through controllable energy input. In this study, the passive envelope does not maintain comfort, and natural ventilation is intermittent due to wind-direction, pressure and timing dependence. This is consistent with Kotireddy et al. (2019), who argue that early design

lacks actionable guidance for combined uncertainty. In the patient-room case, uncertainty concerns not only climate and façade performance, but also infection-control constraints, window operation, internal loads, patient vulnerability, staff routines and local air-speed distribution. A hybrid passive-active strategy is therefore more defensible than a fully passive strategy.

Conventional room-temperature comfort is insufficient for patient rooms

The comfort results validate the need for occupant-specific assessment. Ruggiero et al. (2022) showed that bedridden patients can fall outside comfort limits even when indoor temperatures remain within conventional ISO 7730 summer ranges. Under the same 2050 HVAC baseline, mobile patients remain below the 27°C SET threshold, while bedridden patients and staff exceed it during substantial parts of the summer period (Fig. 4.7). This confirms that T_o alone cannot represent comfort in patient rooms. Thermal response depends on the interaction between T_o , v_{air} , clothing or bedding insulation, MET and exposure pattern. Ruggiero et al. (2022) show that acceptable temperature ranges in hospitals differ per user group when bedding, CLO and reduced patient activity are included: 21.8–27.9°C for patients and only 24.1–25.6°C for medical staff. The simulation results show a similar pattern. In the hybrid scenario, the mobile patient remains within a comfortable range, with an average SET of 25.78°C, while the bedridden patient remains close to the upper patient boundary, with an average SET of 28.86°C. Staff comfort improves the most: although the hybrid strategy reduces average SET from 30.13°C to 27.74°C and exceedance hours from 2148 to 1760, the average SET still exceeds Ruggiero et al. 2022's staff range. The comparison is not exact, because Ruggiero et al. (2022) report temperature ranges while this study uses SET, but both studies confirm that hospital comfort assessment must be differentiated by user group rather than based on one generic indoor temperature band.

The user-group differences are physiologically consistent with Zhang et al. (2020). For bedridden patients, high total insulation from bedding restricts convective and evaporative heat loss. For staff, higher MET increases internal heat production. A respiratory heat-loss check illustrates this mechanism: under $T_{air} = 26^\circ\text{C}$ and $p_a = 1.68\text{ kPa}$, estimated respiratory heat loss is 4.72 W/m² for bedridden patients, 5.99 W/m² for mobile patients and 8.56 W/m² for staff (Eq. 20). The higher value for staff reflects higher metabolism, but does not imply greater comfort, because total metabolic heat production increases more than respiratory heat loss. This supports the simulation outcome: staff benefit strongly from air movement but remain sensitive to heat, while bedridden patients remain constrained by bedding insulation (Fig. 4.17-4.19).

The role of elevated v_{air} is consistent with Song et al. (2021), who report that higher v_{air} can increase acceptable T_o by approximately 2°C in occupant-controlled environments. In the hybrid scenario, local air movement allows the cooling setpoint to increase from 24°C to 26°C while partly compensating the comfort penalty of the higher setpoint. The effect is user-dependent: staff show the strongest improvement, bedridden patients show a lower average SET but persistent exceedance, and mobile patients perform slightly less favourably than the baseline. Natural ventilation shows the same mechanism less reliably: for mobile patients, adding local v_{air} to the sensible-only ventilation case reduces average SET by 0.87°C, from 30.99°C to 30.12°C, with peak reductions of approximately 4.5°C under favourable wind conditions. The dot plots further confirm that, at equal T_o , higher local v_{air} corresponds to lower SET.

SET is therefore a more suitable primary metric than PMV alone for this study, because it captures the combined effect of T_{air} , T_r , humidity, v_{air} , Clo and MET . However, PMV remains useful as a simplified control signal, for example for estimating fan operation and electricity use. This distinction is important: SET supports physiological and comfort interpretation, while PMV can support operational rule-based modelling. PMV-based fan activation should not be read as observed behaviour, especially for staff, whose movement through the room makes continuous local fan exposure unrealistic.

The physiological plausibility check based on Zhang et al. (2020) (Eq. 21) supports the internal consistency of the bedridden-patient results. Using $R_{tr} = 1.43$, $M = 1.057$ met and respiratory heat loss of 4.72 W/m^2 , the left-hand side of the plausibility condition equals 81.12. Under the corrected hybrid scenario, with average $T_a = 24.89^\circ\text{C}$, RH of 57.12% and $p_a \approx 1.80 \text{ kPa}$, the right-hand side equals 15.31. Since $81.12 > 15.31$, the condition is satisfied, indicating that evaporative heat transfer does not unrealistically dominate the heat balance. This is not a full model validation, but it supports the plausibility of the hybrid comfort results under average conditions.

Finally, the staff results are consistent with Derks et al. (2018), who found that nurses may experience slightly warm sensations and reduced work performance at ward temperatures between 20 and 25°C , with a neutral temperature around 21.8°C . This study similarly shows that staff are thermally sensitive in the HVAC baseline and benefit most from elevated air speed in the hybrid scenario, although exceedance above 27°C remains substantial. The comparison remains methodological rather than behavioural: Derks et al. report subjective responses in real wards, while this study uses fixed MET/CLO profiles and simulated comfort indicators. Both nevertheless point to the same conclusion: staff comfort requires explicit attention and cannot be assumed to follow standard room-temperature criteria.

6.1.2 Translating results into a different context

Relation between simulation results and interview findings

The simulation results largely support the interview findings, while adding quantitative specificity. Interviewees identified internal heat gains from equipment, lighting, occupancy and medical technology as a major constraint on passive cooling. This is confirmed by the simulations: despite a substantial reduction in transmitted solar radiation, the passive envelope remains insufficient because lighting and equipment gains dominate the residual heat balance. Passive façade measures therefore cannot be evaluated independently from programme, equipment and operational assumptions.

The findings also clarify the debated role of operable windows. Interviewees valued windows for perceived control and psychological benefit, but technical specialists questioned their climatic reliability and compatibility with controlled systems. The simulations support this caution: natural ventilation is intermittent, with 0 m/s window air speed during 845 hours of the analysed period. However, they also nuance the interview findings by showing that air movement can reduce SET when available or locally generated. This supports the potential of local fans or bed-level airflow, while confirming that hygiene, air mixing, draught and controllability remain critical implementation conditions.

The interviews further show that hospital design is risk-averse, installation-led and dependent on evidence before non-standard strategies are accepted. The simulations substantiate this position: passive measures alone are insufficient, whereas the hybrid scenario provides a more defensible pathway by combining mechanical cooling with occupant-level air movement. Passive cooling should therefore not be framed as a replacement for active systems, but as a quantified, function-specific strategy for reducing system dependency while maintaining operational reliability. Given the uneven interview sample, these findings should be read as contextual validation rather than definitive proof of implementation feasibility.

Transferability to building scale

The simulation was based on a single representative patient room and should therefore be interpreted as a room-scale comparison, not a building-scale prediction. At full-building scale, adjacent rooms, corridors and technical zones may buffer heat transfer and alter peak temperatures. Conversely, repeated rooms, stacked façades and shared technical systems may intensify cumulative heat loads.

Airflow behaviour would also become more complex. Pressure differences, corridor connections, leakage paths, open doors and simultaneous window operation could create interzonal airflow patterns that are not represented in the single-room model. Orientation further limits direct extrapolation: the south-west-facing room represents a relatively critical condition, while north-facing or shaded rooms would likely perform differently. Building-scale application therefore requires spatial differentiation by orientation, floor level, programme, façade exposure and airflow path.

Transferability to other typologies

Transferability to other healthcare typologies is conditional. The interviews suggest that passive strategies may be more feasible in long-term care or residential care settings, where internal heat loads and clinical control requirements are often lower and user control may be more acceptable. In acute hospital wards, however, high equipment loads, 24/7 operation, infection-prevention constraints and standardised installation concepts limit the reliability of fully passive measures.

Even within one hospital, passive-first strategies should be differentiated by function and risk profile. Highly controlled spaces require active fallback and strict air-quality control, while outpatient areas, office-like functions and lower-risk care environments may allow greater use of natural ventilation, adaptive comfort and user control. Beyond healthcare, the findings may inform typologies facing similar tensions between internal heat gains, comfort, reliability and air-quality constraints, but should not be transferred directly. The broader contribution lies in the method: assessing passive potential through internal-load sensitivity, occupant-level comfort and hybrid system dependency rather than assuming universal applicability of a single passive strategy.

6.1.3 Further research

The most urgent next step is validation of local air movement in patient rooms through higher-resolution airflow modelling, such as CFD or zonal airflow models, combined with measurements in mock-up or operational healthcare settings. This is needed because the effectiveness of both natural ventilation and bed-level fan strategies depends on airflow direction, velocity distribution, draught risk, hygiene and clinical acceptability. In addition, the predicted thermal comfort effects should be validated against real occupant responses. The present study uses established comfort indicators to compare scenarios, but uncertainty remains regarding how accurately these indicators represent different patient groups, especially bedridden, elderly or medically vulnerable occupants. Further empirical research is therefore needed on thermal perception, adaptive capacity and acceptable air movement for specific patient groups. This may require the development or refinement of thermal comfort models that better account for bedding insulation, limited mobility, metabolic variability and clinical constraints.

A second priority is full-building and full-year simulation, including orientation diversity, adjacent rooms, corridors, seasonal trade-offs and realistic HVAC performance. Such studies should also test whether room-scale improvements remain effective when integrated into the operational dynamics of a hospital ward. Finally, sensitivity studies on equipment loads, bedding configuration, user behaviour and future weather data are needed to determine when passive and hybrid cooling remains effective across different healthcare functions. Since climate projections and design weather files are periodically updated, overheating risk and cooling performance should be reassessed over time rather than treated as fixed design outcomes.

6.2 Final conclusion

This research investigated how passive and hybrid cooling strategies at patient-room scale can support occupant-centred thermal comfort and reduce cooling demand in Dutch hospital buildings under projected 2050 climate conditions. The main conclusion is that a fully passive patient-room concept is not a robust solution under projected 2050 climate conditions. Passive measures can reduce overheating risk and lower cooling demand, but they do not provide sufficient reliability to replace mechanical cooling in hospital settings. Their performance depends on the interaction between solar heat-gain prevention, internal heat loads, thermal storage, heat dissipation and user-specific heat exchange. In addition, their implementation potential remains limited when introduced as isolated measures, since such strategies are easily overridden by clinical risk concerns, fragmented requirements, cost logic and installation-led decision-making. A passive-first approach is therefore only meaningful as an early-stage design philosophy: layered, occupant-centred, function-specific and explicitly supported by hybrid or mechanical cooling where passive capacity becomes insufficient.

RQ1 addressed the building-physics mechanisms that determine passive cooling performance.

The literature and simulations indicate that patient-room overheating is governed by the full heat balance rather than by façade performance alone. Solar gains, façade orientation, glazing properties and shading determine the external thermal load, while internal gains from equipment, lighting and occupancy can dominate the residual heat balance. Thermal mass can delay and redistribute heat, but does not remove it. Ventilation and air movement are therefore critical because they provide heat dissipation and modify occupant-level convective and evaporative heat loss. Passive cooling performance should consequently be assessed through operative temperature, SET, local air speed and user-specific parameters, rather than through air temperature or cooling demand alone.

RQ2 examined how comfort limits differ between healthcare user profiles.

The results show that a uniform comfort criterion is insufficient for patient rooms. Mobile patients, bedridden patients and staff respond differently to the same indoor conditions because their metabolic rate, clothing or bedding insulation, exposure duration and adaptive capacity differ. Mobile patients generally remain closer to acceptable SET ranges because of lower insulation and greater heat-dissipation potential. Bedridden patients are constrained by bedding insulation and limited exposed body surface, while staff experience high thermal load due to higher metabolic heat production. The same room condition can therefore produce different thermal risks for different users, making occupant-centred comfort assessment essential.

RQ3 assessed the effect of passive envelope measures under projected 2050 climate conditions.

Under the applied assumptions, the passive envelope strongly reduces transmitted solar radiation. However, this does not translate into a proportional comfort improvement. Operative temperature remains high in the free-floating scenarios, even after façade optimisation. This is because internal gains from lighting and equipment remain substantial and become dominant once solar transmission is reduced. The sensitivity analysis suggests that reducing equipment power has a larger effect on operative temperature than reducing occupancy or changing construction type. These numerical outcomes are uncertain because they depend strongly on the assumed internal loads, simplified room model, summer-only period and free-floating setup. Nevertheless, the direction of the finding is robust: passive envelope measures are necessary to reduce external heat gains, but insufficient as a stand-alone overheating mitigation strategy in continuously occupied patient rooms with high equipment loads.

RQ4 examined occupant-level air movement through natural ventilation and local fans.

Natural ventilation improves SET-based comfort only intermittently. In the model, a substantial part of the analysed summer period has little or no calculated wind-driven air speed at the window. This result should not be interpreted as an exact prediction of ventilation availability, because local air speed was derived from simplified pressure-based calculations rather than detailed airflow

simulation. However, it supports the broader conclusion that openable windows cannot be assumed to provide stable cooling in this context. When air speed is available, its comfort effect is clear: local air movement can reduce SET by improving convective and evaporative heat loss, even when room temperature itself is not strongly reduced.

The hybrid scenario provides the strongest indication of the potential value of controlled local air movement. Under the tested assumptions, raising the mechanical cooling setpoint from 24°C to 26°C while adding local fans substantially reduces ideal cooling demand, roughly in the order of two-thirds, and reduces active cooling hours by about half. These values should be interpreted cautiously: they represent ideal cooling loads, not final electricity use, and depend on the assumed COP, fan control logic, local air-speed calculation and simplified HVAC representation. The comfort effect is also user-dependent. Staff benefit most from elevated air speed because of their higher metabolic rate, while bedridden patients show a smaller improvement because bedding insulation restricts heat dissipation. The result therefore supports the principle of local air movement and setpoint flexibility, but not a fixed universal fan strategy for all users.

RQ5 addressed how simulation evidence and stakeholder findings can inform early-stage design guidance. The interviews show that passive cooling is not primarily blocked by a lack of technical options. The dominant barriers are control uncertainty, infection-prevention concerns, unclear ownership, fragmented PvE requirements, short-term cost logic and an installation-led design culture. The simulation results reinforce this finding: passive measures alone are not sufficiently robust under the tested conditions, while hybrid strategies are more defensible because they combine passive reduction of heat loads with controllable active fallback. Early-stage design guidance should therefore translate simulation outputs into decision-relevant indicators, including comfort robustness, user-specific thermal risk, cooling-load reduction, airflow controllability, spatial implications, operational reliability and long-term value. A clear project ambition and an explicit responsibility holder are essential to keep passive strategies active throughout the design process.

The main research question can therefore be answered as follows: Passive and hybrid cooling strategies can support occupant-centred comfort and reduce cooling demand in Dutch hospital patient rooms when applied as a layered strategy rather than as isolated measures. The projected 2050 weather conditions substantially increase thermal stress, indicating that future climate data should be included explicitly in early design assessment. Solar control reduces external heat gains, but must be combined with internal-load reduction, heat dissipation and local air movement. Natural ventilation can provide useful comfort benefits, but its availability is uncertain and intermittent. Local fans or bed-level air movement can make the air-speed benefit more controllable and may support higher mechanical cooling setpoints, particularly for active users and potentially for fixed patient positions. However, energy and cost reductions must account for fan electricity use, which is difficult to predict because actual operation depends on user behaviour, comfort preferences, clinical acceptability and control logic. Mechanical cooling therefore remains necessary, but its role can shift from default low-temperature full-room conditioning towards hybrid fallback for the remaining demand.

The conclusions from the simulation study should be interpreted with considerable uncertainty. The model represents one simplified patient room, not a full hospital building. Interzonal heat transfer, corridor interaction, façade repetition, orientation diversity, detailed window frames, thermal bridges and surrounding context were simplified. Airflow was estimated through pressure-based calculations and post-processing rather than CFD or detailed airflow modelling. The analysis was limited to the summer period and used an hourly timestep, which smooths short-term wind, solar and window-operation effects. User profiles were represented by fixed metabolic rates and insulation values, while actual clothing, bedding, posture, control behaviour and care routines may vary. The interview findings are also indicative rather than statistically representative because the stakeholder sample was diverse and uneven.

Despite these uncertainties, the research provides a consistent design message. Patient-room cooling under future climate conditions should not rely on either conventional low-temperature mechanical cooling or passive measures alone. The most defensible pathway is a passive-first, hybrid strategy: reduce solar gains, critically manage internal loads, preserve thermal buffering capacity, create predictable and clinically acceptable airflow paths and use targeted local air movement to reduce perceived heat stress while allowing higher cooling setpoints where appropriate. In this framing, passive cooling becomes not merely an energy-saving measure, but a design philosophy that links building physics, user vulnerability and healthcare decision-making from the earliest project stages.

6.3 Reflection

How is my graduation topic positioned in the studio: climate design within building technology

My graduation topic is positioned within the climate design domain of Building Technology because it addresses the relation between thermal comfort, passive cooling, façade performance, ventilation strategies, energy use, and technical decision-making in healthcare buildings. Rather than treating climate design as a purely technical calculation, the research investigates how passive cooling strategies can become part of the design process of complex buildings such as hospitals.

The topic fits the studio because it combines building physics with design-oriented questions. Passive cooling is not only about lowering temperatures or reducing cooling demand, but also about spatial consequences, user comfort and risk. In healthcare buildings, these aspects are especially critical because comfort and safety are directly related to vulnerable users, staff performance, and continuity of care.

At the same time, the topic turned out to be broader and more complex than I initially expected. Hospitals are highly specific buildings, and many passive strategies depend strongly on interlinked considerations. This made the research relevant, but also difficult to translate into one detailed design solution.

How did the research approach work out?

The research approach combined literature review, simulation, stakeholder interviews, and design-oriented recommendations. This worked well because passive cooling in hospitals cannot be understood from a single perspective. The literature provided the theoretical basis, the simulations clarified the building-physical effects, and the interviews showed why certain strategies are difficult to implement in practice.

The approach also had clear limitations. Each method produced a different type of knowledge. The simulations gave quantitative results, while the interviews were qualitative and context-dependent. Bringing these together required interpretation, and therefore also introduced subjectivity. Especially because some stakeholder groups were represented by only one participant. The simulations were useful since they showed that passive envelope measures can strongly reduce solar gains, but that this does not automatically solve overheating. Internal heat loads, 24/7 occupancy, and heat accumulation remained important. This made the research more critical: passive cooling cannot simply replace mechanical cooling, but needs to be understood as part of a broader strategy.

During the process, I seriously considered several times whether I should analyse a design option using CFD. I read extensively about the possibilities of CFD for ventilation and thermal comfort research, especially for studying air movement around patients. However, I decided not to include it

in the final method because the required level of modelling detail, boundary conditions, validation, and interpretation is very high. Without sufficient accuracy, CFD results can easily appear convincing while not being reliable enough to support strong conclusions. I also questioned whether, within the available time, it would be possible to make a detailed model that would genuinely convince stakeholders that a passive or hybrid measure works in a hospital context.

Looking back, I think this was a reasonable decision, but also a missed opportunity. If more time had been available, CFD would have been a logical next step, especially to study the breathing zone of bedbound patients and the local effect of a bed-integrated fan and controlled local air movement. In hospital environments, evidence-based arguments are important to make passive measures credible in the design process. A carefully validated CFD analysis could therefore have strengthened the technical and persuasive value of the research.

Did it lead to the results I aimed for?

The research produced valuable results, although not entirely the type of outcome I initially expected. I had hoped to arrive at a more technical final product, such as a detailed passive cooling strategy, a tested design proposal, or a specific technical application for a hospital room. Instead, the outcome developed into a design framework supported by simulations, interviews, barriers and drivers, and process-oriented recommendations.

This shift occurred for two main reasons. First, the research showed that passive cooling is broader than a set of technical measures. It must be integrated early in the project, including the brief, stakeholder discussions, comfort definitions, room-specific requirements, cost evaluations and operational decisions. As a result, the conclusions naturally moved towards design-process recommendations rather than one isolated technical solution.

Secondly, the research addressed many aspects of the topic: literature, simulations, interviews, stakeholder perspectives, barriers and drivers, design recommendations and practice. This broad approach helped to understand passive cooling in healthcare from multiple angles and created a strong connection with practice. At the same time, it reduced the technical depth. A narrower study could have examined specific strategies, simulations or design details more rigorously.

The results were therefore different from what I expected, but they answered the research problem in a realistic way. The study does not prove that one passive cooling solution works for all hospital contexts. Instead, it shows that passive cooling only becomes meaningful when it is embedded in a broader design process. This was not my initial expectation, but it became one of the main findings of the research.

In retrospect, one technical direction could have been developed further, for example through a detailed case-study design or CFD analysis. This would have made the final product more technical and easier to evaluate. However, a purely technical outcome might have missed the larger issue revealed by the research: passive cooling in hospitals is not only limited by performance, but also by decision-making, risk perception and implementation conditions.

Was my method in line with methods used in other climate design research?

My method was partly in line with climate design research because it used literature review and building performance simulation. These methods are common within building physics and environmental design research.

However, my research also included stakeholder interviews and design-process analysis. This made the method broader than a conventional performance study. I think this was necessary because the

6. DISCUSSION, CONCLUSION AND REFLECTION

main question was not only whether passive cooling measures can perform technically, but also why they are or are not considered in real healthcare projects.

This broader approach fits the applied character of Building Technology, but it also made the research less clean methodologically. The simulation results could be assessed directly, while the interview findings required interpretation. A stronger version of the method would include more interviewees per stakeholder group and a more explicit validation step, for example through expert review validation, or further CFD analysis of one promising design direction.

How are research and design related in my research?

Research and design were related, but not always equally balanced. The research strongly informed the design thinking: literature defined the passive cooling principles, simulations showed where passive measures were effective or insufficient, and interviews revealed practical barriers and drivers. These findings were translated into recommendations and a design framework but the design itself remained relatively conceptual and explorative. Instead of developing one detailed technical solution, I mainly designed a way of thinking and deciding: how passive cooling could be discussed earlier, evaluated per room type, and weighed against comfort, risk, costs, and technical feasibility. This was valuable, but it also meant that the project leaned more towards research and framework development than towards detailed design.

The main reason for this was the context-dependency of the topic. A passive cooling solution in a hospital depends on many variables, such as façade orientation, patient type, infection prevention level, internal loads, user control, and operational protocols. I was hesitant to design something too specific, because I did not want to suggest that one solution could be broadly applicable.

Looking back, I think I could have accepted this context-dependency more explicitly and used it as part of the design research. A detailed Erasmus MC-based design would not have needed to be universal. It could have functioned as a test case to explore how the framework works in practice. This would have made the relationship between research and design stronger and more visible.

Did I encounter moral or ethical issues or dilemmas during the process?

Several ethical dilemmas appeared during the research. The most important one was that passive cooling in hospitals cannot be judged only by sustainability or energy performance. Hospitals serve vulnerable users, and thermal comfort, air quality, infection prevention, and reliability directly affect patient wellbeing and staff performance. A passive measure that is acceptable in an office building may not be responsible in a patient room without further evidence.

This created a tension between sustainability ambition and operational safety. I had to be careful not to present passive cooling as inherently better. Passive measures can reduce energy use and improve resilience, but if they are poorly designed or insufficiently controlled, they may also introduce discomfort, uncertainty, or risk.

Another dilemma concerned user comfort. Climate requirements in hospitals are often written from a technical and maintenance perspective, while patients and staff may experience comfort in more personal and varied ways. This raised the question of whose comfort is prioritised and how much individual control is acceptable in a healthcare setting.

The interviews also involved ethical responsibility. Since I spoke to a limited number of stakeholders, I had to avoid generalising individual statements too strongly. Their input was valuable, but represents specific professional perspectives within specific contexts.

7

REFERENCES

7. REFERENCES

- [1] Aflaki, A., & Jarrahi, A. (2025). Application of airfoil arrays on building façades as a passive design strategy to improve indoor ventilation. *Architecture*, 5(3), 64. <https://doi.org/10.3390/architecture5030064>
- [2] Allard, F., & Santamouris, M. (1998, February 15). Natural ventilation in buildings - a design handbook. <https://www.osti.gov/etdeweb/biblio/20730457>
- [3] Anand, V., Kadiri, V. L., & Putcha, C. (2023). Passive buildings: state-of-the-art review. *Journal of Infrastructure Preservation and Resilience*, 4(1). <https://doi.org/10.1186/s43065-022-00068-z>
- [4] Arowoia, V. A., Onososen, A. O., Moehler, R. C., & Fang, Y. (2024). Influence of thermal comfort on energy consumption for building occupants: the current state of the art. *Buildings*, 14(5), 1310. <https://doi.org/10.3390/buildings14051310>
- [5] ASHRAE, "Physiological Principles and Thermal Comfort" *ASHRAE Handbook Fundamentals*, 1993 American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2012). ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2010: Thermal environmental conditions for human occupancy.
- [6] ASHRAE. https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/55_2010_d_published.pdf
- [7] Attia, S. (2018). Net zero energy buildings: Concepts, frameworks and roadmap. *Elsevier*. <https://doi.org/10.1016/C2016-0-00175-9>
- [8] Attia, S., Gratia, E., De Herde, A., & Hensen, J. L. (2012). Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings*, 49, 2–15. <https://doi.org/10.1016/j.enbuild.2012.01.028>
- [9] Balali, A., & Valipour, A. (2020). Prioritization of passive measures for energy optimization designing of sustainable hospitals and health centres. *Journal of Building Engineering*, 35, 101992 <https://doi.org/10.1016/j.jobe.2020.101992>
- [10] Beck, H., Zimmermann, N., McVicar, T. et al. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci Data* 5180214 (2018). <https://doi.org/10.1038/sdata.2018.214>
- [11] Betgen, C., Boekhold, S., Boomsma, C., A, V. D., Hall, E., & Hagens, W. (2024). Gezondheidseffecten van klimaatverandering. Actualisatie van de huidige klimaatrisico's voor gezondheid. In *Rivm (National Institute for Public Health and the Environment)*, 30-31. <https://doi.org/10.21945/rivm-2023-0324>
- [12] Bhatia, A., Dontu, S., Garg, V., & Singh, R. (2024). Approach for energy efficient building design during early phase of design process. *Energy Informatics*, 7(1). <https://doi.org/10.1186/s42162-024-00426-z>
- [13] Butaro District Hospital. (n.d.). MASS. <https://modelofarchitecture.org/projects/butaro-district-hospital>
- [14] Boerstra, A. C., Van Heumen, S. P. M., Huisman, E. R. C. M., Kompatscher, K., Kort, H. S. M., TU Delft, TNO, Hogeschool Utrecht, BBA Binnenmilieu BV, TU Eindhoven, De Kort, J., Te Kulve, M., Loomans, M. G. L. C., & Traversari, A. A. L. (2021). Rapport Onderzoek naar eisen voor het binnenklimaat in de langdurige zorg <https://www.expertisecentrumverduurzamingzorg.nl/kennisbank/rapport-onderzoek-eisen-binnenklimaat-langdurige-zorg/>
- [15] Boerstra, A. C., Van Heumen, S. P. M., Jacobs, P., Kompatscher, K., Kort, H. S. M., De Kort, J. M. A., Te Kulve, M., Loomans, M. G. L. C., & Traversari, A. A. L. (2024). Programma van Eisen Gezond Binnenklimaat Langdurige zorg - Binnenklimaattechniek. In *Binnenklimaattechniek*. <https://www.binnenklimaattechniek.nl/kennisbank/programma-van-eisen-gezond-binnenklimaat-langdurige-zorg/>
- [17] Bouzidi, Y., Akili, Z. E., Gademer, A., Tazi, N., & Chahboun, A. (2021). How can we adapt thermal comfort for disabled patients? A case study of French healthcare buildings in summer. *Energies*, 14(15), 4530. <https://doi.org/10.3390/en14154530>
- [18] Centraal Bureau Voor Statistiek, (2025, December 12a). Dossier Broeikasgassen. CBS. <https://www.cbs.nl/nl-nl/cijfers/detail/84979NED?q=broeikasgassen>
- [19] Centraal Bureau voor de Statistiek, (2025, December 16b). Bevolkingsprognose: vanaf nu meer ouderen dan jongeren. Centraal Bureau Voor De Statistiek. <https://www.cbs.nl/nl-nl/nieuws/2025/51/bevolkingsprognose-vanaf-nu-meer-ouderen-dan-jongeren>
- [20] CIBSE Journal. (2023, October 23). Module 208: Room air distribution for effective ventilation - *CIBSE Journal*. <https://www.cibsejournal.com/cpd/modules/2022-12-air/>
- [21] Day & Son./Library of Congress, Washington, D.C. (LC-USZC4-10261)
- [22] de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104(Part 1), 145-167.
- [23] Fanger, P. O. (1970). Thermal comfort: Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press. ISBN 87-571-0170-4
- [24] Gagge, J.A.J. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, *Build. Eng.* 77 (1) (1971) 21–36
- [25] Gittler, A. B. M., & Lam, S. S. (2025). Decision making and decision support during the design of healthcare Facilities: A Systematic review. *Buildings*, 15(14), 2474. <https://doi.org/10.3390/buildings15142474>
- [26] Givoni, B. (1994). Passive low energy cooling of buildings. John Wiley & Sons.
- [27] Hamdy, M., Carlucci, S., Hoes, P., & Hensen, J. L. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Building and Environment*, 122, 307–323. <https://doi.org/10.1016/j.buildenv.2017.06.031>
- [28] Heiranipour, M., Juaristi, M., Avesani, S., & Favoino, F. (2025). Towards early-stage facade design for heat resilient buildings: impact of weather file generation for office buildings in temperate climates. *Building and Environment*, 284, 113459. <https://doi.org/10.1016/j.buildenv.2025.113459>
- [29] Hodder, S. G., & Parsons, K. (2006). The effects of solar radiation on thermal comfort. *International Journal of Biometeorology*, 51(3), 233–250. <https://doi.org/10.1007/s00484-006-0050-y>
- [30] Hoffmann, C., Liebers, U., Humbsch, P., Drozdek, M., Bölke, G., Hoffmann, P., Holzgreve, A., Donaldson, G. C., & Witt, C. (2021). An adaptation strategy to urban heat: hospital rooms with radiant cooling accelerate patient recovery. *ERJ Open Research*, 7(3), 00881–02020. <https://doi.org/10.1183/23120541.00881-2020>
- [32] Hopfe, C. J., & Hensen, J. L. (2011). Uncertainty analysis in building performance simulation for design support. *Energy and Buildings*, 43(10), 2798–2805. <https://doi.org/10.1016/j.enbuild.2011.06.034>
- [33] Huizenga, C., Zhang, H., Schiavon, S., Kwong, L. H., Brager, G., Arens, E., Roa, C. D., Exss, K., Luna-Navarro, A., & Authors, N. M. (2024). Establishing maximum safe indoor temperatures for U.S. residential buildings. TU Delft Research Portal. <https://research.tudelft.nl/en/publications/establishing-maximum-safe-indoor-temperatures-for-us-residential/>

7. REFERENCES

- [34] Hunt, G. R., Linden, P. F., & Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge, CB3 9EW, U.K. (1999). The fluid mechanics of natural ventilation-displacement ventilation by buoyancy-driven flows assisted by wind. *Building And Environment*, 34, 707–720. <https://paul-linden.com/wp-content/uploads/2017/05/68hl99.pdf>
- [35] Infoblad Trias Energetica en energieneutraal bouwen. (2013). In *Rijksdienst Ondernemend Nederland*, Rijksdienst Ondernemend Nederland. <https://www.rvo.nl/sites/default/files/2023-11/infoblad-trias-energetica-en-energieneutraal-bouwen.pdf>
- [36] International Energy Agency EBC Annex 80, Institute of Building Research & Innovation, Zhang, C., Heiselberg, P., Brunel University, Kolokotroni, M., Salvati, A., Chalmers University of Technology, Arghand, T., Javed, S., ENEA Italian National Agency, Zinzi, M., Hunan University, Ai, Z., Zhang, G., Institute of Building Research & Innovation, Stern, P., Holzer, P., KU Leuven, . Sodagar, B. (2022). *Resilient cooling of buildings State of the art review* (P. Holzer & P. Stern, Eds.). <https://doi.org/10.52776/COXK4763>
- [37] ISO 7730 – 1995, “Moderate thermal environments.” Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.
- [38] Kalz, D. E., & Pfafferott, J. (2014). Thermal comfort and energy-efficient cooling of nonresidential buildings (pp. 2-8). Cham, Germany: Springer International Publishing.
- [39] KNMI. (2023). KNMI’23 Klimaatscenario’s. In KNMI. <https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s>
- [40] Konis, K., Gamas, A., & Kensek, K. (2016). Passive performance and building form: An optimization framework for early-stage design support. *Solar Energy*, 125, 161–179. <https://doi.org/10.1016/j.solener.2015.12.020>
- [41] Kotireddy, R., Loonen, R., Hoes, P., & Hensen, J. L. (2019). Building performance robustness assessment: Comparative study and demonstration using scenario analysis. *Energy and Buildings*, 202, 109362. <https://doi.org/10.1016/j.enbuild.2019.109362>
- [42] Konstantinou, T., & Prieto Hoces, A. (2018). Environmental Design Principles for the Building Envelope and More _: Passive and Active Measures. In T. Konstantinou, N. Cukovic, & M. Zbasnik (Eds.), *Energy Resources and Building Performance* (pp. 147-180). (Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design). TU Delft OPEN Publishing. <https://books.bk.tudelft.nl/index.php/press/catalog/book/isbn.9789463660341>
- [43] Kwon, M., Remøy, H., Van Den Dobbelsteen, A., & Knaack, U. (2018). Personal control and environmental user satisfaction in office buildings: Results of case studies in the Netherlands. *Building and Environment*, 149, 428–435. <https://doi.org/10.1016/j.buildenv.2018.12.021>
- [44] Laouadi, A., Ji, L., Shu, C., Wang, L., & Lacasse, M. (2023). Overheating risk Analysis in Long-Term Care Homes—Development of overheating limit Criteria. *Buildings*, 13(2), 390. <https://doi.org/10.3390/buildings13020390>
- [45] Van Der Linden, A. C., Kuijpers-Van Gaalen, I. M., Zeegers, A., DGMR, Central Government Real Estate Agency, Van Der Linden, A. C., Selten, T. A. J., moBius consult b.v., Van Herpen, R. H. P., & Nieman Raadgevende Ingenieurs. (2024). Building Physics (A. C. Van Der Linden & M. J. C. Van Der Klooster, Eds.; 2024.1). Faculty of Architecture and the Built Environment. <https://klimapedia.nl/wp-content/uploads/2024/07/Building-Physics-2024.1.pdf>
- [46] Lomas, K. J., & Porritt, S. M. (2016). Overheating in buildings: lessons from research. *Building Research & Information*, 45(1–2), 1–18. <https://doi.org/10.1080/09613218.2017.1256136>
- [47] Lu, S., Li, J., & Lin, B. (2019). Reliability analysis of an energy-based form optimization of office buildings under uncertainties in envelope and occupant parameters. *Energy and Buildings*, 209, 109707. <https://doi.org/10.1016/j.enbuild.2019.109707>
- [48] MacLeamy, P. (2004). Designing for the future: BIM and the design profession. American Institute of Architects.
- [49] Maghami, M. R., Maghoul, A., Thang, K. F., & Sundaram, S. (2025). Net zero energy buildings: An overview of passive and active designs. *Energy Reports*, 14, 1327–1348. <https://doi.org/10.1016/j.egy.2025.07.028>
- [50] Meade, R. D., Notley, S. R., Kirby, N. V., & Kenny, G. P. (2024). A critical review of the effectiveness of electric fans as a personal cooling intervention in hot weather and heatwaves. *The Lancet Planetary Health*, 8(4), e256–e269. [https://doi.org/10.1016/s2542-5196\(24\)00030-5](https://doi.org/10.1016/s2542-5196(24)00030-5)
- [51] Medved, S. (2022). Building Physics: Heat, ventilation, moisture, light, sound, fire, and urban microclimate. Springer. <https://doi.org/10.1007/978-3-030-74390-1>
- [52] NEN-ISO. (2017). NEN-ISO 15686-5:2017 En. <https://www.nen.nl/nen-iso-15686-5-2017-en-236967>
- [53] Van Paassen, A. H. C. (2004). Fundamental aspects of thermal comfort (L. C. M. Itard & P. M. Bluyssen, Eds.). https://ocw.tudelft.nl/wp-content/uploads/Thermal_Comfort_Reader__Comfort_and_Health_in_Buildings.pdf
- [54] Paimio Sanatorium - Alvar Aalto Foundation | Alvar Aalto -säätio EN. (2025, November 20). Alvar Aalto Foundation | Alvar Aalto -säätio EN. <https://www.alvaraalto.fi/en/architecture/paimio-sanatorium/>
- [55] Panchalingam, K., Debacker, W., De Troyer, F., & Van Passel, S. (2024). Cost-related drivers and barriers of Passivhaus: A systematic literature review. *Sustainability*, 16(15), 6510. <https://doi.org/10.3390/su16156510>
- [56] Pitts, A. (2017). Passive House and Low Energy Buildings: Barriers and Opportunities for Future Development within UK Practice. *Sustainability*, 9(2), 272. <https://doi.org/10.3390/su9020272>
- [57] Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018). Passive cooling & climate responsive façade design. *Energy and Buildings*, 175, 30–47. <https://doi.org/10.1016/j.enbuild.2018.06.016>
- [58] Raji, B., Tenpierik, M. J., Bokel, R., & Van Den Dobbelsteen, A. (2019). Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. *International Journal Of Ventilation*, 19(1), Low 25–48. <https://doi.org/10.1080/14733315.2018.1524210>
- [59] Rijksoverheid. (2022). Green Deal Duurzame Zorg 3.0. In Green Deal Duurzame Zorg. Green deal duurzame zorg. <https://www.greendealduurzamezorg.nl/green-deal-duurzame-zorg/>
- [60] Santamouris, M., & Kolokotsa, D. (2012). Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy and Buildings*, 57, 74–94. <https://doi.org/10.1016/j.enbuild.2012.11.002>

7. REFERENCES

- [61] Shen, J., Kong, M., Dong, B., Birnkrant, M. J., & Zhang, J. (2021). A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2. *Building and Environment*, 200, 107926. <https://doi.org/10.1016/j.buildenv.2021.107926>
- [62] Song, C., Duan, G., Wang, D., Liu, Y., Du, H., & Chen, G. (2021). Study on the influence of air velocity on human thermal comfort under non-uniform thermal environment. *Building and Environment*, 196, 107808. <https://doi.org/10.1016/j.buildenv.2021.107808>
- [63] Steenmeijer, M. A., Pieters, L. I., Warmenhoven, N., Huiberts, E. H. W., Stoelinga, M., Zijp, M. C., RIVM, Van Zelm, R., & Waaijers-van Der Loop, S. L. (2022). The impact of Dutch healthcare on the environment. In RIVM Report 2022-0159 (pp. 2–144). National Institute for Public Health and the Environment, RIVM. <https://doi.org/10.21945/RIVM-2022-0159>
- [64] Tang, Y., Yu, H., Zhang, K., Niu, K., Mao, H., & Luo, M. (2022). Thermal comfort performance and energy-efficiency evaluation of six personal heating/cooling devices. *Building and Environment*, 217, 109069. <https://doi.org/10.1016/j.buildenv.2022.109069>
- [65] Tartarini, F., Cooper, P. and Fleming, R. “Thermal perceptions, preferences and adaptive behaviours of occupants of nursing homes,” *Build Environ*, vol. 132, pp. 57-69, 2018, doi: 10.1016/j.buildenv.2018.01.018
- [66] Teng, X., Oo, M. L., Ge, J., Wong, N. H., & Fan, Y. (2025). The improvement of wind comfort and natural ventilation in high-rise building vertical gardens with adjustable louver angles. *Building and Environment*, 285, 113638. <https://doi.org/10.1016/j.buildenv.2025.113638>
- [67] Vbnb. (2025, October 21). Zonnestraal Hilversum - STEENGOED HILVERSUM. STEENGOED HILVERSUM. <https://steengoedhilversum.nl/monumenten/zonnestraal-hilversum/#>
- [68] Yuan, F., Yao, R., Sadrizadeh, S., Li, B., Cao, G., Zhang, S., Zhou, S., Liu, H., Bogdan, A., Croitoru, C., Melikov, A., Short, C. A., & Li, B. (2021). Thermal comfort in hospital buildings – A literature review. *Journal of Building Engineering*, 45, 103463. <https://doi.org/10.1016/j.jobbe.2021.103463>
- [69] Zarco-Soto, F. J., Zarco-Soto, I. M., Ali, S. S. S., & Zarco-Periñán, P. J. (2025). Energy consumption in buildings: A compilation of current studies. *Energy Reports*, 13, 1293–1307. <https://doi.org/10.1016/j.egy.2024.12.069>
- [70] Zhang, C., Kazanci, O. B., Levinson, R., Heiselberg, P., Olesen, B. W., Chiesa, G., Sodagar, B., Ai, Z., Selkowitz, S., Zinzi, M., Mahdavi, A., Teufl, H., Kolokotroni, M., Salvati, A., Bozonnet, E., Chtioui, F., Salagnac, P., Rahif, R., Attia, S., Zhang, G. (2021). Resilient cooling strategies – A critical review and qualitative assessment. *Energy and Buildings*, 251, 111312. <https://doi.org/10.1016/j.enbuild.2021.111312>
- [71] Zhao, D., Aili, A., Zhai, Y., Xu, S., Tan, G., Yin, X., & Yang, R. (2019). Radiative sky cooling: Fundamental principles, materials, and applications. *Applied Physics Reviews*, 6(2). <https://doi.org/10.1063/1.5087281>
- [72] Zhou, J., Zhang, X., Xie, J., & Liu, J. (2023). Effects of elevated air speed on thermal comfort in hot-humid climate and the extended summer comfort zone. *Energy and Buildings*, 287, 112953. <https://doi.org/10.1016/j.enbuild.2023.112953>

8

APPENDICES

A. Literature review search query

		no filter	filter 10 years	filter: 5 years	filter: English, engineering, environmental science, energy, Physics, multidisciplinary
Broad exploration query	("passive and active strategies" OR "hybrid building systems" OR "integrated design") AND ("energy performance" OR "thermal comfort" OR "occupant comfort" OR "life cycle cost") AND ("healthcare buildings" OR "patient wards" OR "care homes") AND ("simulation" OR "building performance simulation" OR "energy modeling" OR "parametric study") AND ("Netherlands" OR "Dutch climate" OR "temperate climate")	2459	2256	1798	1690
Focused query (comfort-energy-cost balance)	("passive and active strategies" OR "hybrid building systems" OR "integrated design") AND ("energy performance" OR "thermal comfort" OR "occupant comfort" OR "life cycle cost") AND ("healthcare buildings" OR "patient wards" OR "care homes") AND ("simulation" OR "building performance simulation" OR "energy modeling" OR "parametric study") AND ("Netherlands" OR "Dutch climate" OR "temperate climate")	15	15	10	-
Targeted (simulation-based exploration in Dutch healthcare context)	("simulation-based design" OR "parametric modeling" OR "building performance simulation") AND ("passive strategies" AND "active systems") AND ("thermal comfort" AND "energy use" AND "cost") AND ("healthcare building" OR "patient ward" OR "care home") AND ("Netherlands" OR "Dutch context" OR "urban climate")	0	-	-	-
more balanced (iteration 1)	("passive design" OR "passive strategies" OR "building envelope" OR "natural ventilation") AND ("active systems" OR HVAC OR "mechanical ventilation" OR "heating cooling systems" OR "building services") AND ("energy efficiency" OR "thermal comfort" OR "indoor environmental quality") AND ("healthcare buildings" OR "hospitals" OR "care homes" OR "patient wards") AND ("simulation" OR "building performance simulation" OR "energy modeling" OR "parametric study") AND ("temperate climate" OR "Netherlands" OR "Dutch climate")	278	264	219	214

Fig. A.1: Search query analysis used for literature review

B. Design uncertainties

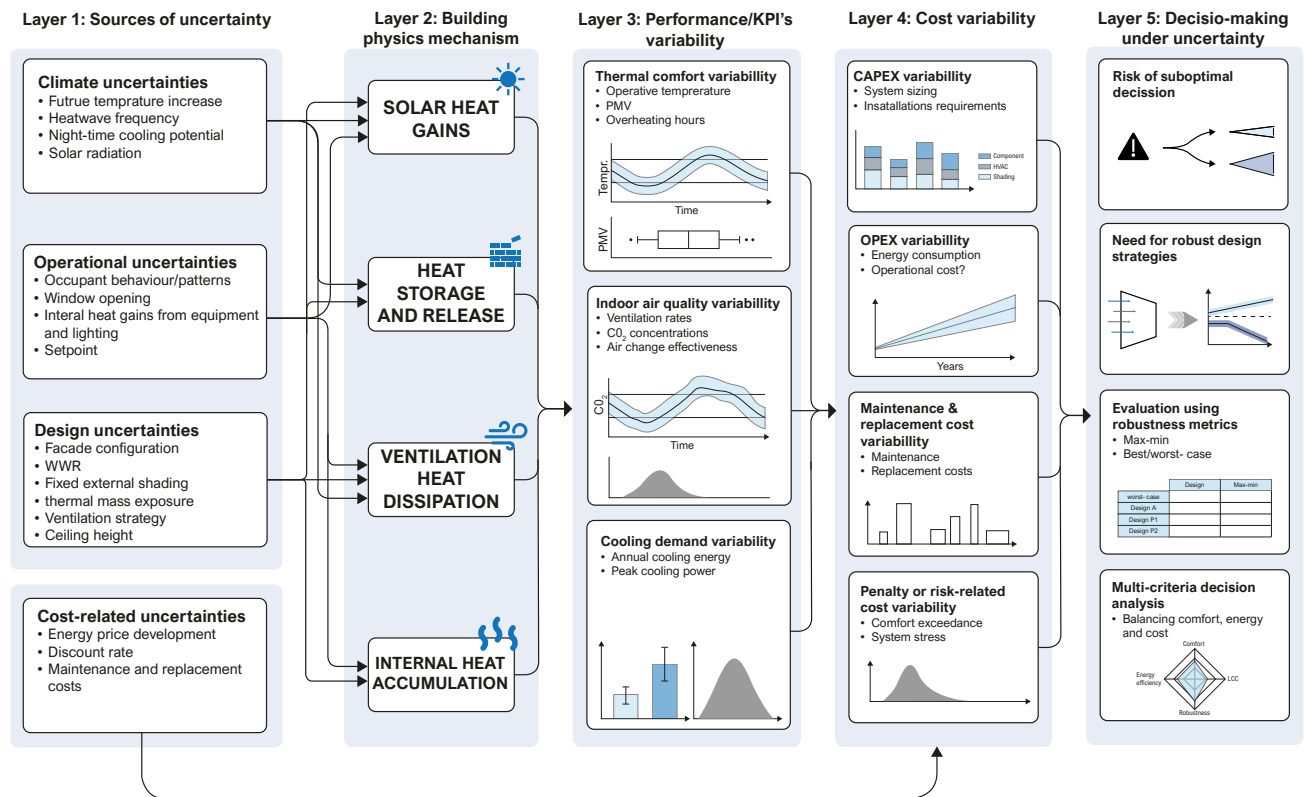


Fig. B.1: Preliminary overview of the design uncertainties involved in passive design strategies. (Author's work)

C. PMV/PPD formulas

$$PMV = (0,303 \cdot e^{-0,031 \cdot M^*} + 0,028) \cdot [RM^* - 3,05 \cdot 10^{-3} \cdot (5733 - 6,99 \cdot RM^* - p_i) - 0,42 \cdot (RM^* - 58,15) - 17 \cdot 10^{-6} \cdot M^* \cdot (5867 - p_i) - 1,4 \cdot 10^{-3} \cdot M^* \cdot (34 - T_i) - 39,6 \cdot 10^{-9} \cdot f_{kl} \cdot ((T_{kl} + 273)^4 - (T_s + 273)^4) - f_{kl} \cdot \alpha_c \cdot (T_{kl} - T_i)]$$

$$PPD = 100 - 95e^{-0.03353PMV^4 - 0.2179PMV^2}$$

D. Temperature setpoints by research

Type document	Document / Source	User group	Temperature parameter	Recommended range	Country / Context	Notes
Standard	EN 16798-1 (Category I)	Vulnerable occupants	Operative temperature (winter)	approx. 21–23 °C	EU	Category I intended for sensitive occupants
Standard	ISO 7730 (Category A/B)	Staff (healthy)	Operative temperature	approx. 23–26 °C (cooling season)	International	Comfort-based (PMV ±0.2/0.5)
Standard	ASHRAE 55	General occupancy	Operative temperature	~23–26 °C (depending on clo/met)	USA	Comfort model-based
Healthcare standard	ASHRAE 170	Standard patient room	Air temperature (design)	21–24 °C (70–75 °F)	USA	Clinical design temperature
Healthcare guideline	FGI Guidelines	Standard patient room	Air temperature (design)	21–24 °C	USA	Refers to ASHRAE 170
Healthcare standard	HTM 03-01	Standard patient room	Air temperature	18–28 °C	UK	Operational envelope
Standard	DIN 4108-2	Residential / vulnerable	Indoor air temperature (max)	≤27 °C	Germany	Overheating criterion
Standard	TM59 (CIBSE)	Vulnerable occupants	Max indoor air temperature	26 °C adaptive threshold	UK	Overheating assessment (residential reference)
Research synthesis	CR 1752 (1998)	Hospital ward	Air temperature	20–26 °C	EU	Referenced in hospital temperature compilations
Research synthesis	Shajahan et al., 2019	Hospital ward	Air temperature	20–26 °C	International review	Compilation of ward requirements
Research	Lomas & Ji (2013)	Healthy occupants	Max indoor air temperature (8h)	28 °C	UK	Overheating study
Research	Lomas & Ji (2013)	Vulnerable occupants	Max indoor air temperature (8h)	26 °C	UK	Reduced tolerance
Research	Zhang et al., 2022	Bedridden patient (1.9 clo, 40 W/m²)	Operative temperature (neutral)	≈24.8 °C	Italy	Model-based neutral temp
Research	Derks et al., 2018	Staff	Neutral air temperature	21.8 °C	NL	Field study

Table D.1: Indoor room temperatures recommended by literature and standards.

E. Masterplan Erasmus MC 2050

MASTERPLAN 2050



Fig. D.1: Masterplan 2050 for Case study Erasmus MC (Erasmus, 2026)

F. Year-round weather analysis for de Bilt, 2050

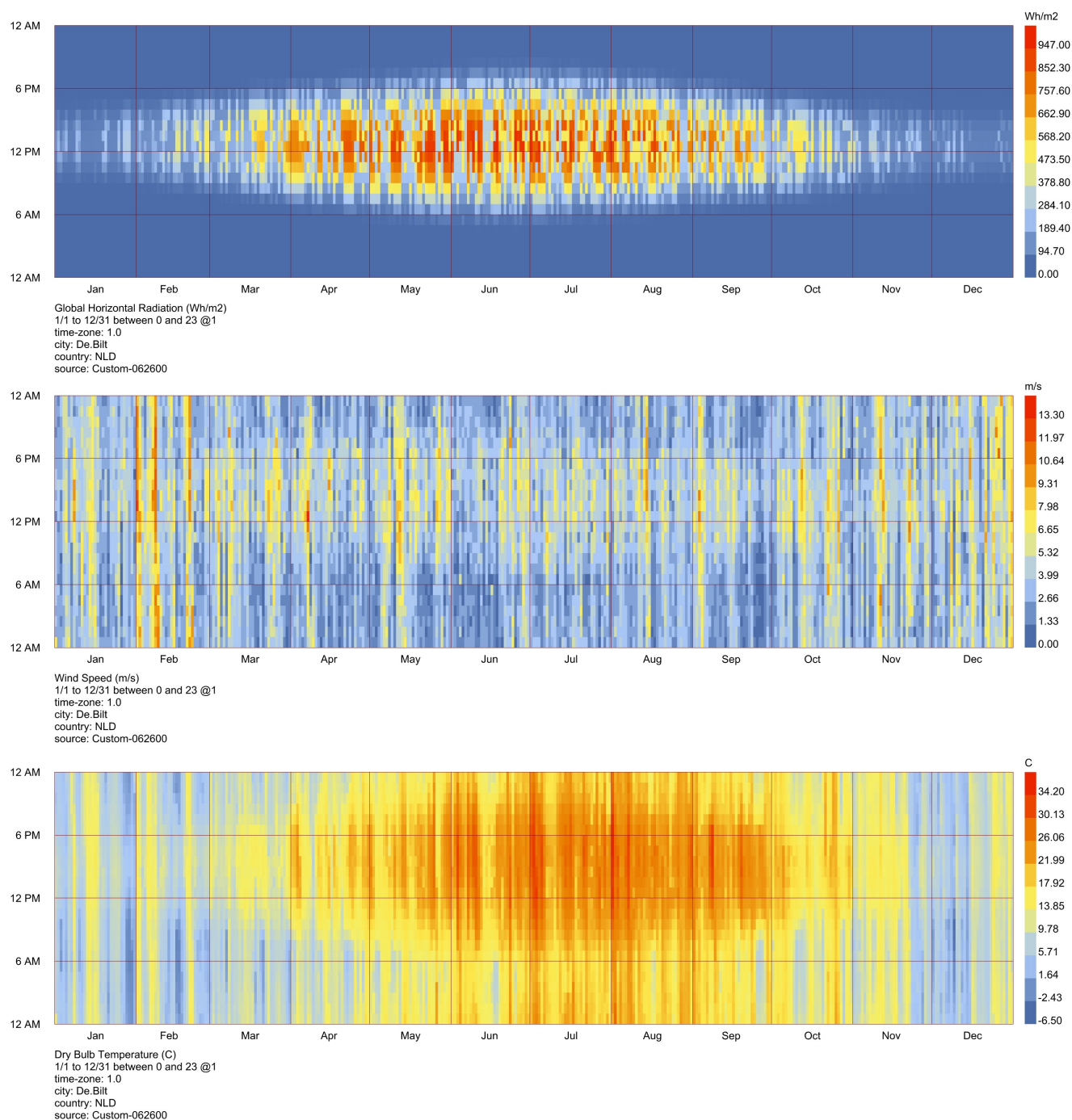


Fig. F.1: Yearly hour plot for Global horizontal radiation, windspeed and dry bulb temperature for 2050, using morphed EPW

G. Detailed construction sets for simulation

Name	Value	Validation
Construction exterior wall	STUCCO thickness {m}: 0.0253 Conductivity {W/m-K}: 0.691 density {kg/m³}: 1858.004 Specific heat {J/kg-K}: 836.460 Thermal absorptance 0.9 Solar absorptance: 0.7 visible absorptance: 0.92 CONCRETE Thickness {m}: 0.2032 Conductivity {W/m-K}: 1.310 Density {kg/m³}: 2240.005 Specific heat {J/kg-K}: 836.260 Thermal absorptance: 0.9 solar absorptance: 0.7 Visible absorptance: 0.7 TYPICAL INSULATION-R3 r-value {m²-K/W}: 0.528 thermal absorptance 0.9 solar absorptance: 0.7 visible absorptance: 0.7 GYPSUM thickness {m}: 0.0127 conductivity {W/m-K}: 0.160 density {kg/m³}: 784.902 specific heat {J/kg-K}: 829.465 thermal absorptance: 0.9 solar absorptance: 0.4 visible absorptance: 0.4	DOE reference building
Construction window	THEORETICAL GLASS thickness {m}: 0.003 solar transmittance: 0.331 solar reflectance front/back: 0.619 visible transmittance: 0.44 visible reflectance front/back: 0.51 infrared_transmittance: 0.0 emissivity front/back: 0.9 conductivity {W/m-K}: 0.133 dirt correction factor: 1.0 solar diffusing: NO	DOE reference building
Construction interior walls	GYPSUM BOARD thickness {m}: 0.013 conductivity {W/m-K}: 0.16 density {kg/m³}: 800.0 specific heat {J/kg-K}: 1090.0 thermal absorptance: 0.9 solar absorptance: 0.5 visible absorptance: 0.5 AIR GAP thickness {m}: 0.1 conductivity {W/m-K}: 0.667 density {kg/m³}: 1.28 specific heat {J/kg-K}: 1000.0 thermal absorptance: 0.9 solar absorptance: 0.7 visible absorptance: 0.7 GYPSUM BOARD thickness {m}: 0.013 conductivity {W/m-K}: 0.16 density {kg/m³}: 800.0 specific heat {J/kg-K}: 1090.0 thermal absorptance: 0.9 solar absorptance: 0.5 visible absorptance: 0.5	DOE reference building

Table G.1: Construction sets for case study simulation detailed version

H. Occupancy schedules case study simulation

Time period	Default/Sunday	Saturday	Weekday
00:00–07:00	0.05	0.10	0.10
07:00–08:00	0.05	0.20	0.50
08:00–16:00	0.10	0.40	0.90
16:00–18:00	0.05	0.40	0.30
18:00–23:00	0.05	0.10	0.30
23:00–00:00	0.05	0.10	0.10

Table H.1: Fractional hourly lighting schedule used in the simulation model.

Time period	Sunday / Default	Saturday	Weekday
00:00–07:00	0.26	0.35	0.35
07:00–08:00	0.26	0.49	0.68
08:00–16:00	0.35	0.63	0.88
16:00–18:00	0.26	0.63	0.58
18:00–22:00	0.26	0.35	0.58
22:00–23:00	0.26	0.35	0.52
23:00–00:00	0.26	0.35	0.35

Table H.2: Fractional hourly equipment schedule used in the simulation model.

Time period	Occupancy / Default
00:00–06:00	0.50
06:00–07:00	0.50
07:00–10:00	0.80
10:00–16:00	1.00
16:00–19:00	0.80
19:00–00:00	0.50

Table H.3: Fractional hourly occupancy schedule used in the simulation model.

I. Critical hours during summer period

$$\text{Stress index} = W_t \cdot T_{\text{norm}} + W_I \cdot I_{\text{norm}} + W_v \cdot (1 - V_{\text{norm}})$$

The weighting factors used here were: temperature 0.4, irradiance 0.4, and wind 0.2. Hours with the highest criticality scores represent the most severe heat stress conditions. When analysing the simulation results, the extreme hours will also be examined.

Date + hours	Stress index
1-8-2050 12:00	0.892409
1-8-2050 11:00	0.865388
1-8-2050 14:00	0.841279
2-7-2050 14:00	0.84019
3-7-2050 11:00	0.83144
3-6-2050 14:00	0.826464
3-6-2050 13:00	0.822758
3-6-2050 12:00	0.822423
3-7-2050 12:00	0.820938
1-8-2050 15:00	0.807888

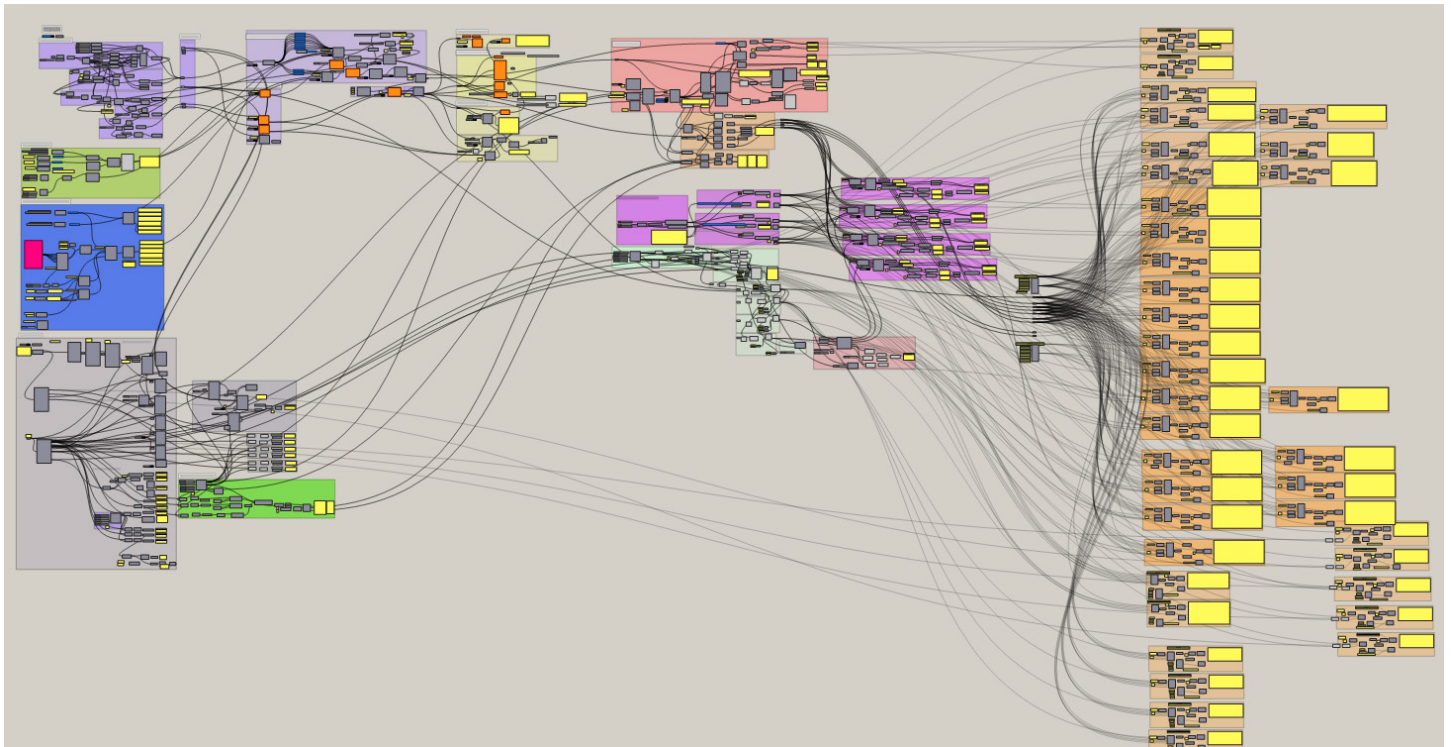
Table I.1: Critical hours + stress index

J. Simulation model simplifications

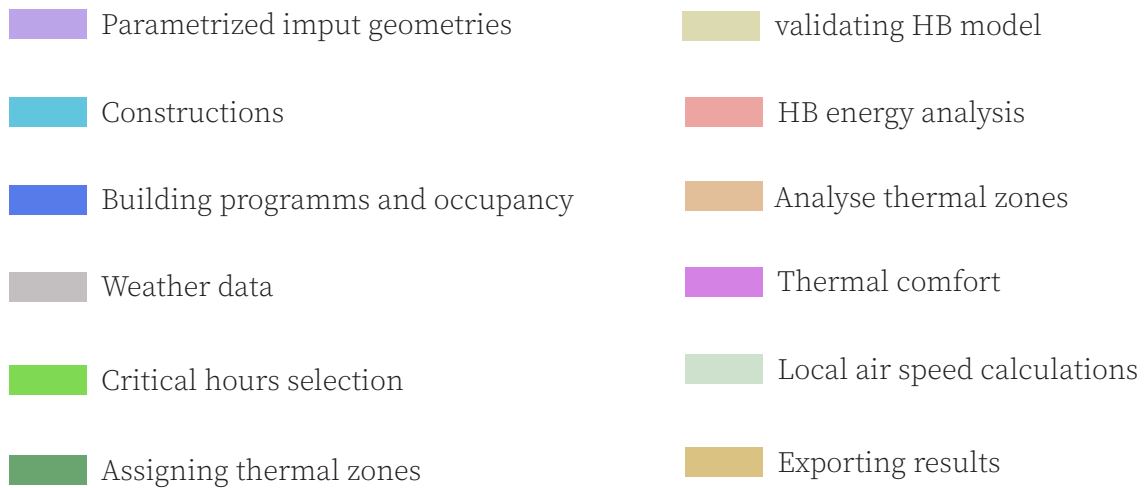
To reduce computational time so that it fits within the time scope of a thesis, various simplifications have been made to the model. This is also partly due to various limitations of Grasshopper and EnergyPlus:

- Single representative patient room modelled at an intermediate floor level, surrounded by eight explicitly modelled adjacent spaces (corridor and neighbouring patient rooms), while all other bounding surfaces were defined as adiabatic.
- Sanitary spaces were excluded from the thermal model, as these are assumed to be mechanically ventilated under all operational scenarios. This might neglect potential thermal buffering effects from adjacent wet rooms.)
- Interior doors were modelled as closed opaque partitions, due to limitations in EnergyPlus regarding stable simulation of interior airflow through open doorways. This likely reduces interzonal air exchange and may overestimate temperature gradients and overheating risk in the patient room.
- Envelope constructions were derived from a DOE reference building and adapted to represent a contemporary Dutch hospital context.
- Internal electrical equipment loads were updated from reference values to reflect contemporary plug-load intensities.
- Occupancy was represented by simplified deterministic schedules, assuming continuous patient presence and time-dependent staff activity.
- Thermal zones were assumed to be well-mixed air volumes, following the EnergyPlus single-node zone air model. This neglects local air temperature stratification and microclimatic variations near façades or ventilation openings.
- Local air velocities associated with natural ventilation strategies were not dynamically simulated in EnergyPlus, but introduced later in the comfort assessment as assumed boundary conditions. This approach captures perceived cooling effects but does not model the direct impact of airflow on zone heat balance.
- Natural ventilation through operable windows was represented using simplified control schedules and airflow assumptions. Actual airflow depends on wind pressure distribution, occupant behaviour, and façade leakage, which introduces uncertainty in predicted cooling potential.
- Shading and solar control elements were modelled as idealised geometric devices without detailed material or operational dynamics.
- Mechanical conditioning in reference scenarios was represented by idealised HVAC control with fixed temperature setpoints. This provides a stable performance benchmark but does not reflect real system dynamics, part-load inefficiencies, or control delays.
- Furniture, medical equipment geometry, and internal layout complexity were not explicitly modelled in radiative or airflow calculations. This may lead to minor deviations in mean radiant temperature distribution and airflow obstruction effects.

K. Grasshopper script



Fig, K.1: Snapshot from Grasshopper script.



L. Derivation of window and shading dimensions

- Façade orientation: south-west
- Evaluation period: summer months
- Maximum accepted direct solar penetration: 2.5 m
- Accepted exceedance: limited late-afternoon period or early mornings
- Fixed external shading devices (no dynamic control)
- Window required to provide outward view for both patient and staff positions

Window height

The window height was defined from the required visual field rather than from solar optimisation alone. The glazing was positioned to allow outward view from both a patient lying in bed and standing staff. This resulted in a window height of $H=1.0$ m

with an assumed sill height of $z_{sill}=0.90$ m, and therefore a glazing head height of:

$$z_{head} = z_{sill} + H = 0.90 + 1.00 = 1.90 \text{ m}$$

Horizontal overhang depth

The horizontal overhang was sized using the solar profile-angle relation:

$$D = \frac{z_{head}}{\tan(\Omega)} - x$$

where:

D = horizontal overhang depth

z_{head} = height of the top of the glazing above floor level

x = maximum accepted solar penetration depth

Ω = critical façade profile angle

$$D = \frac{1.90}{\tan(33^\circ)} - 2.50$$

$$D = 0.43 \text{ m}$$

Vertical fin calculation

The vertical fins were sized using the horizontal shadow-angle relation:

$$F = \frac{W/2}{\tan(HSA)}$$

F = vertical fin depth

W = window width

HSA = horizontal shadow angle

The window width was set at: 2 m

A critical horizontal shadow angle of approximately 70 was used to reduce late-afternoon oblique solar penetration while keeping the fins architecturally feasible.

$$F = \frac{2.0/2}{\tan(70^\circ)}$$
$$F = 0.36 \text{ m}$$

The selected critical solar angles were not derived through full annual optimisation, but through first-order reasoning based on the expected critical summer sun conditions for a south-west oriented façade. The critical profile angle of approximately 33 was selected to limit direct solar penetration during the majority of occupied summer afternoon hours, while still allowing daylight access and maintaining feasible overhang dimensions. Angles below this value mainly occur during low late-afternoon sun conditions, which were considered acceptable for a limited duration.

Similarly, the critical horizontal shadow angle of approximately 70 was selected to target highly oblique late-afternoon solar incidence typical for south-west façades in summer. Reducing solar exposure beyond this range would require disproportionately deep vertical fins, which was considered spatially and architecturally undesirable.

M. Estimation of v_{air} at window and occupant

Estimation of wind pressure on facade

The wind pressure acting on the south-west façade at a height of 20 m was estimated using the wind pressure equation:

$$\Delta P = \frac{1}{2} \rho v_z^2 C_p(\theta)$$

Where ρ is the air density, v_z is wind speed at facade height and $C_p(\theta)$ is the façade pressure coefficient corrected for wind incidence angle. The wind speed at 20 m was derived from the measured wind speed at 10 m using the power-law profile:

$$v_z = v_{10} \left(\frac{z}{10} \right)^\alpha$$

With $V_{10} = 3.72$ m/s (Appendix F), $z = 20$ m and urban terrain exponent $\alpha = 0.22$. The facade wind at patientroom height becomes $v_{20} \approx 4.34$ m/s. Air density was estimated from the measured barometric pressure using the ideal gas law:

$$\rho = \frac{p}{RT} \approx 1.20 \text{ kg/m}^3$$

Considering the average wind direction (224.9°) and the façade orientation deviation (23.5°), the wind approaches the façade at an incidence angle of approximately $\theta = 23^\circ$. The pressure coefficient was therefore corrected using:

$$C_p(\theta) = C_{p,0} \cos^2(\theta)$$

Assuming $C_{p,0} = 0.6$ gives for a straight wind gives $C_p = 0.51$. Substituting these values results in an estimated average façade pressure of: $\Delta P \approx 5.8$ Pa.

Translation to local air speed at occupant positions

The calculated façade pressure was translated into an estimated air speed at the window opening using the orifice relation:

$$v_{\text{window}} = C_d \sqrt{\frac{2\Delta P}{\rho}}$$

where v_{window} is the air speed through the window opening, C_d the discharge coefficient, ΔP the pressure difference across the opening and ρ the air density. The resulting opening velocity was then translated to local air speeds at the three sensor locations using a simplified jet-decay relation:

$$v_i = f_i v_{\text{window}} \left(\frac{x_0}{x_i} \right)^\beta$$

Where v_i is the estimated local air speed at sensor point i , x_i the distance from the window opening to the sensor point x_0 , the reference distance near the opening β the jet-decay exponent and f_i a correction factor for airflow direction and local positioning relative to the main airflow path. This method provides a first-order estimate of occupant-level air speed and should not be interpreted as a resolved room-airflow simulation.

Sensor point A represents the window zone and is therefore assumed to experience the opening air speed directly. Sensor points B and C represent the bed position and staff zone and are corrected for distance-dependent velocity decay and their position relative to the primary airflow path.

N.1 Day-night Drybulb & radiance averages 2025 versus 2050

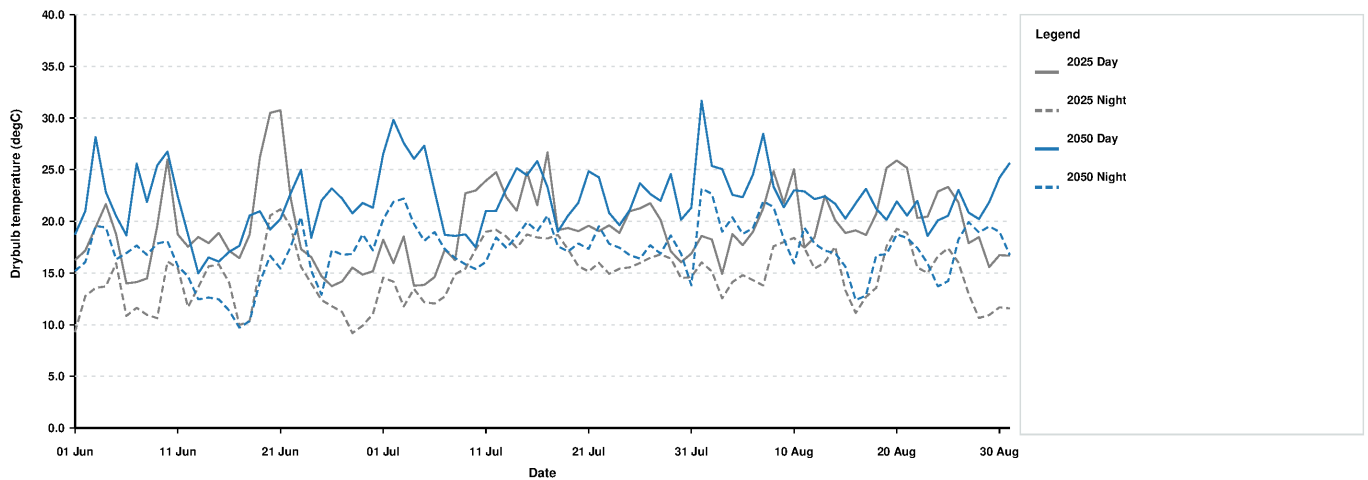


Table N.1.1: Day and night averages plot over summer period for 2025 and 2050

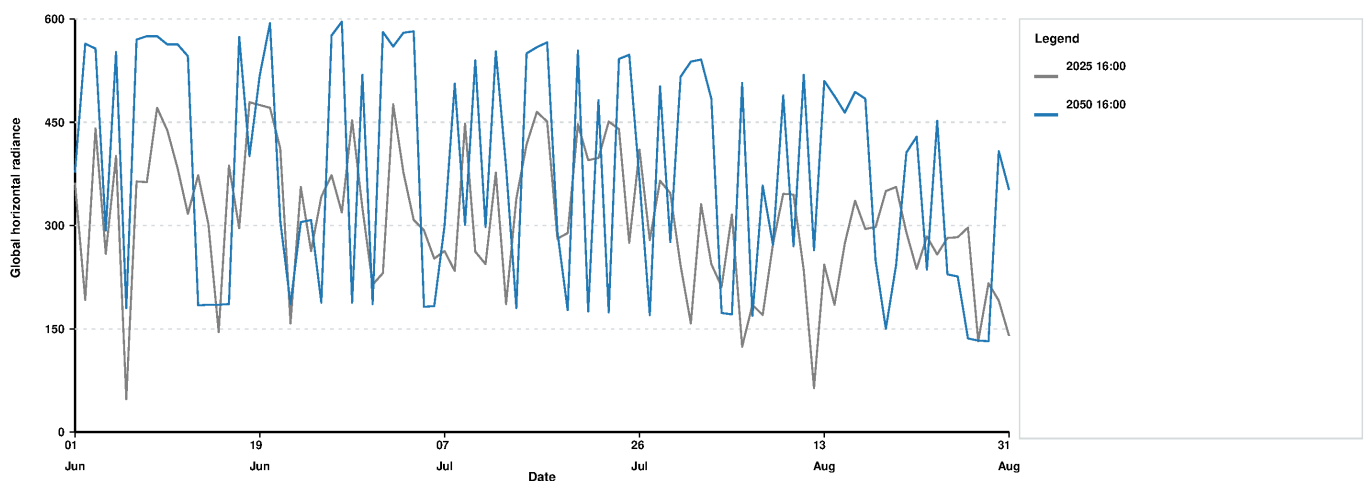


Table N.1.2: Global horizontal radiance at 16:00 over summer period for 2025 and 2050

Freefloating	Value	Passive envelope	Value	
Solar radiation transmittance	11.97 kWh/m ²	Solar radiation transmittance	2.38 kWh/m ²	- 80.1%
End use lighting	5.06 kWh/m ²	End use lighting	5.06 kWh/m ²	
End use equipment	8.65 kWh/m ²	End use equipment	8.65 kWh/m ²	
End use cooling	0 kWh/m ²	End use cooling	0 kWh/m ²	
Hours active cooling	0 h	Hours active cooling	0 h	
Yearly cooling kwh	0 kWh	Yearly cooling kwh	0 Kwh	
Peak cooling	0 watt	Peak cooling	0 watt	
t _o average	42.9 °C	t _o average	38.9 °C	
t _{air} average	43.1 °C	t _{air} average	39.1 °C	
T _{rad} average	42.8 °C	T _{rad} average	38.7 °C	
RH average	95,0%	RH average	100%	

Table N.1.3: Summary tables on energy and thermal comfort performance for freefloating and passive envelope scenario

N.2 Hourly PPD HVAC baseline 2025

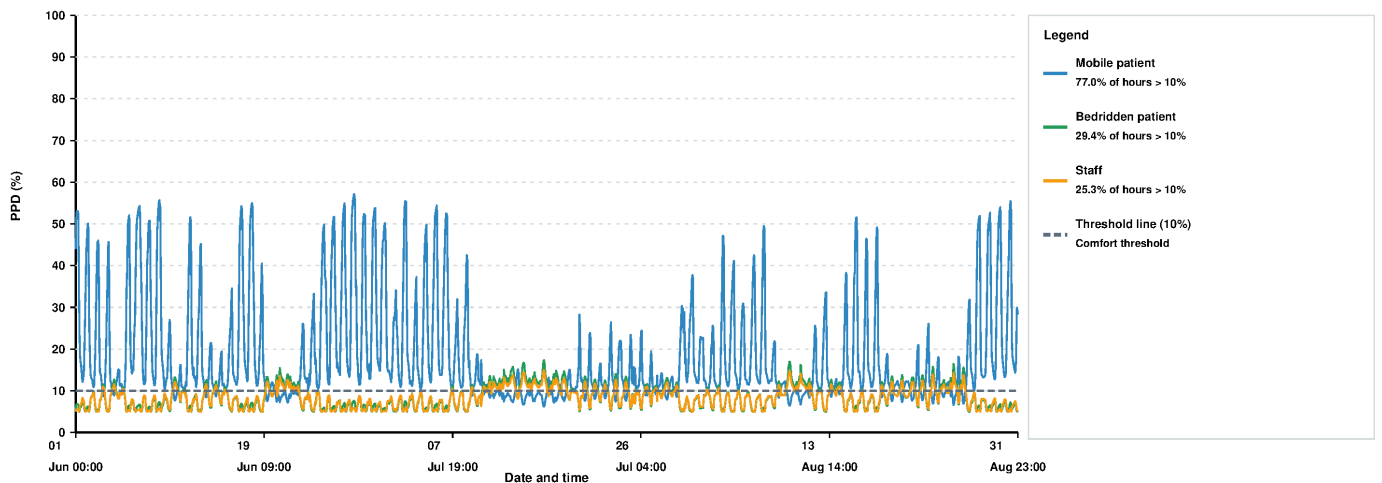


Fig. N.2.1: Hourly PPD for HVAC scenario summer period 2025 for Mobile patient, Bedridden patient and staff. High PPD mobile patient due to low PMV values, occupants feel slightly cool

N.3 Hourly SET and PPD HVAC baseline 2050

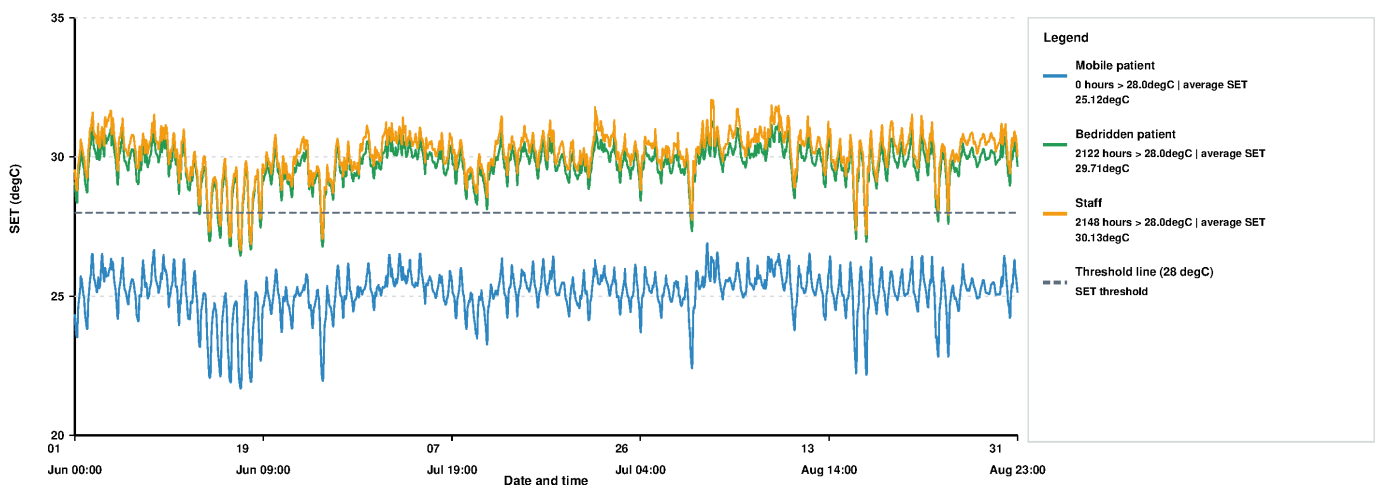


Fig. N.3.1: Hourly SET for HVAC scenario summer period 2050 for Mobile patient, Bedridden patient and staff.

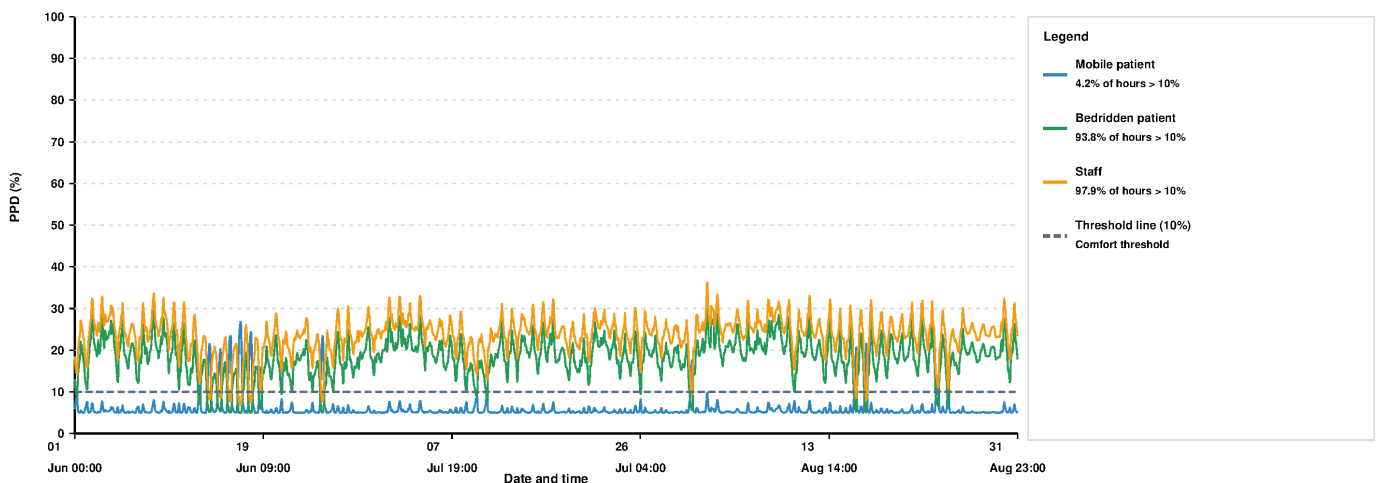


Fig. N.3.2: Hourly PPD for HVAC scenario summer period 2050 for Mobile patient, Bedridden patient and staff.

N.4 Additional results Passive envelope

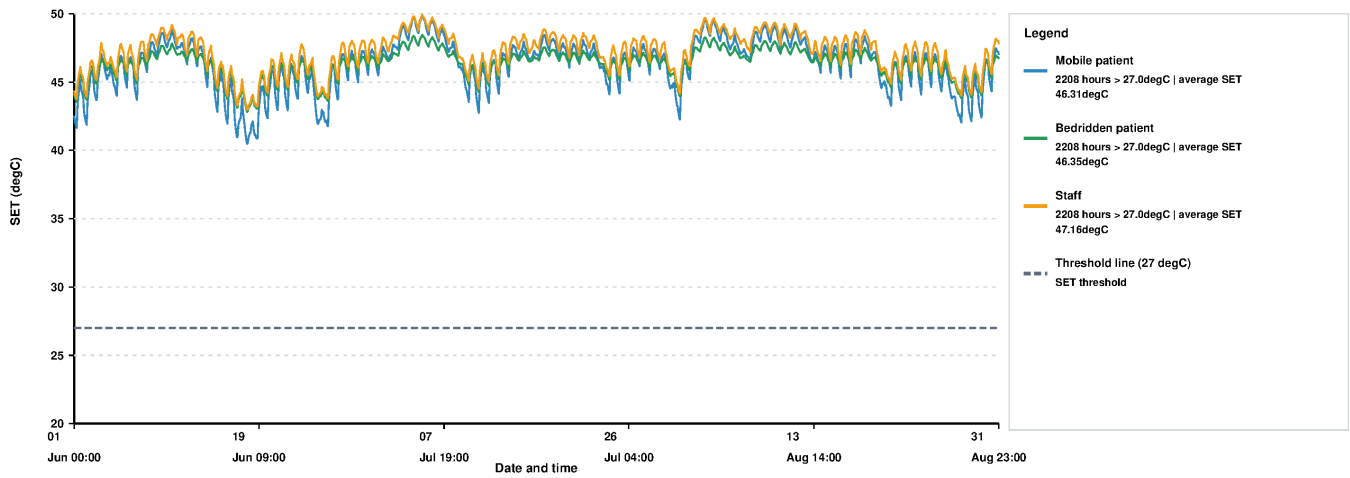


Fig. N.4.1: Hourly SET for Passive envelope scenario summer period 2050 for Mobile patient, Bedridden patient and staff.

N.5 Airspeed at occupants location

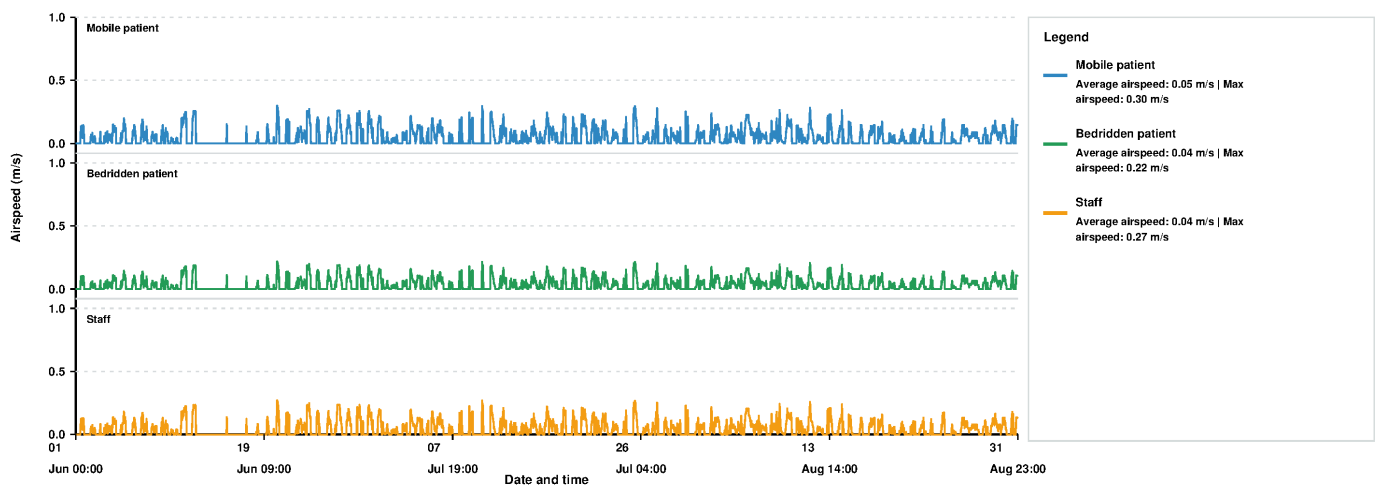


Fig. N.5.1: Hourly V_{air} at occupant locations for summer period 2050.

N.6 Additional results hybrid scenario

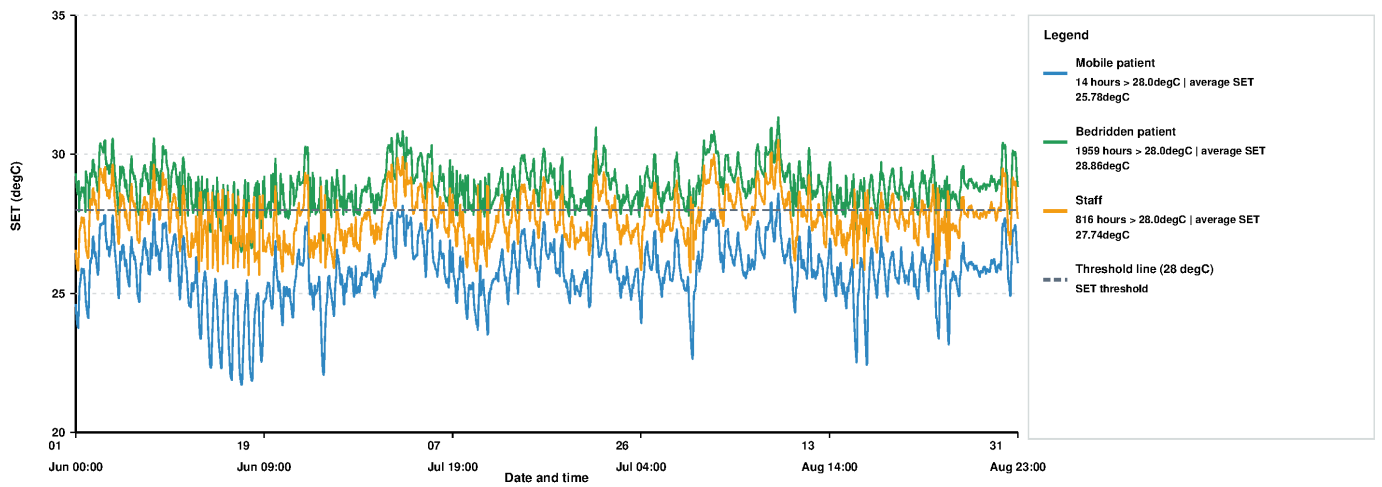


Fig.N.6.1: Hourly SET for Hybrid scenario summer period 2050 for Mobile patient, Bedridden patient and staff.

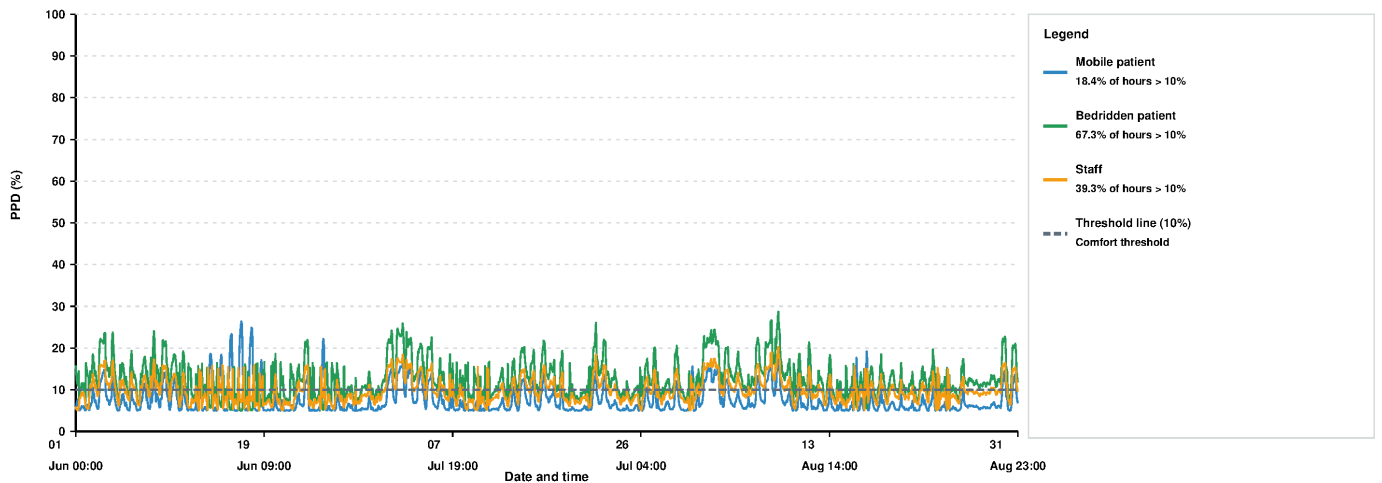


Fig. N.6.2: Hourly PPD for Hybrid scenario summer period 2050 for Mobile patient, Bedridden patient and staff.

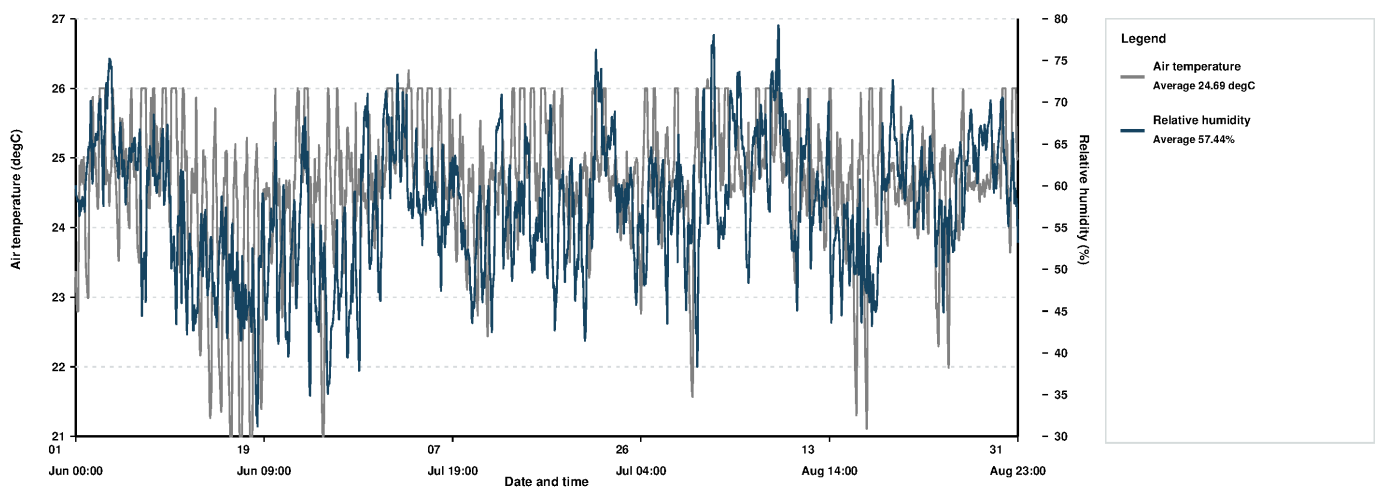


Fig. N.6.3: Hourly $T_{a,indoor}$ and RH for Hybrid scenario 2050.

N.7 Summary SET and PPD comparison over scenarios

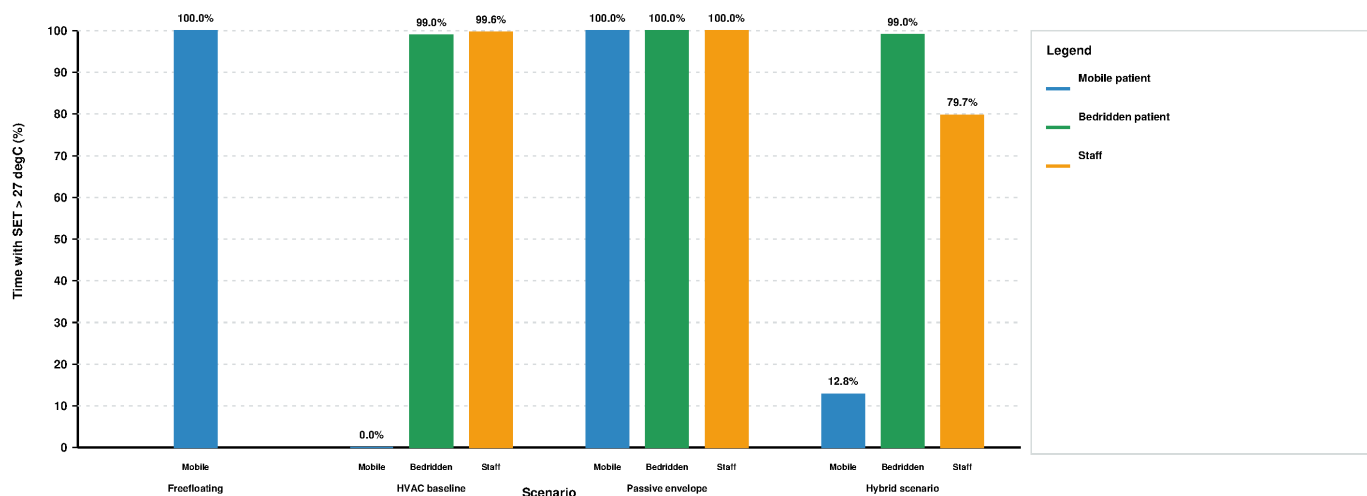


Fig. N.7.1: Summary of SET > 27 deg for all scenarios and user groups 2050

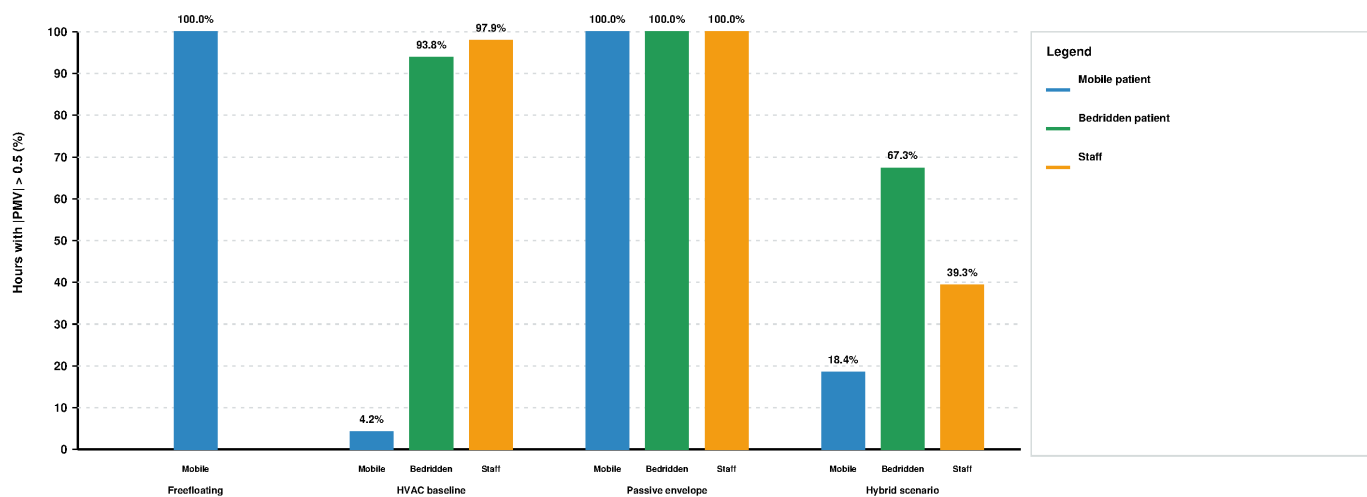


Fig. N.7.2: Summary of hours with |PMV| > 0.5 (above 10% PPD) for all scenarios and user groups 2050

N.8 Hourly SET over all scenarios for different user groups

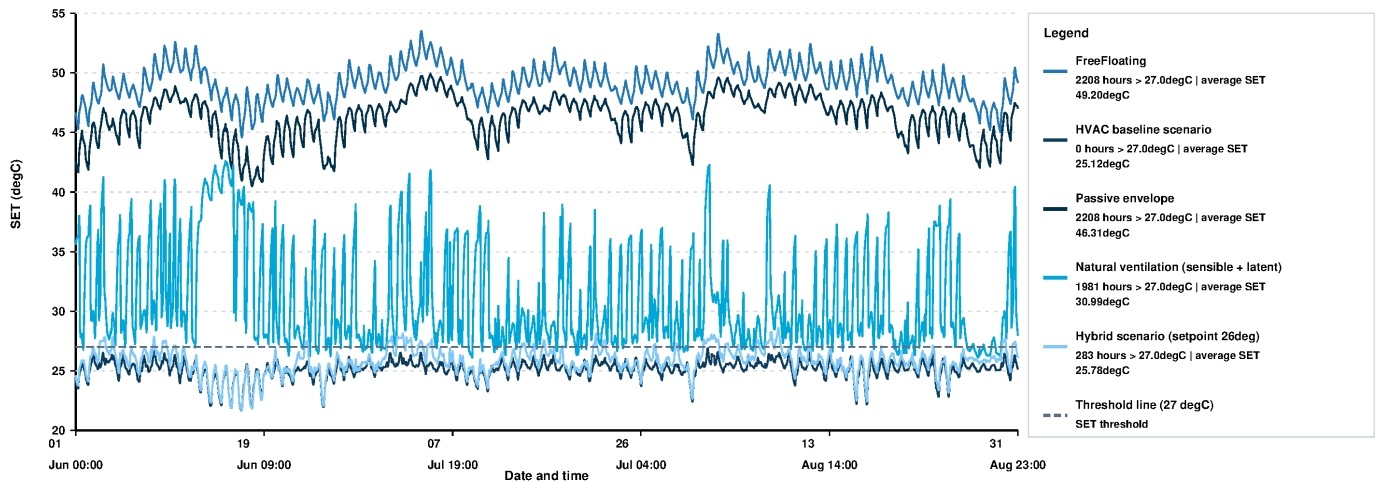


Fig. N.8.1: Comparison hourly SET for all scenarios (mobile patient)

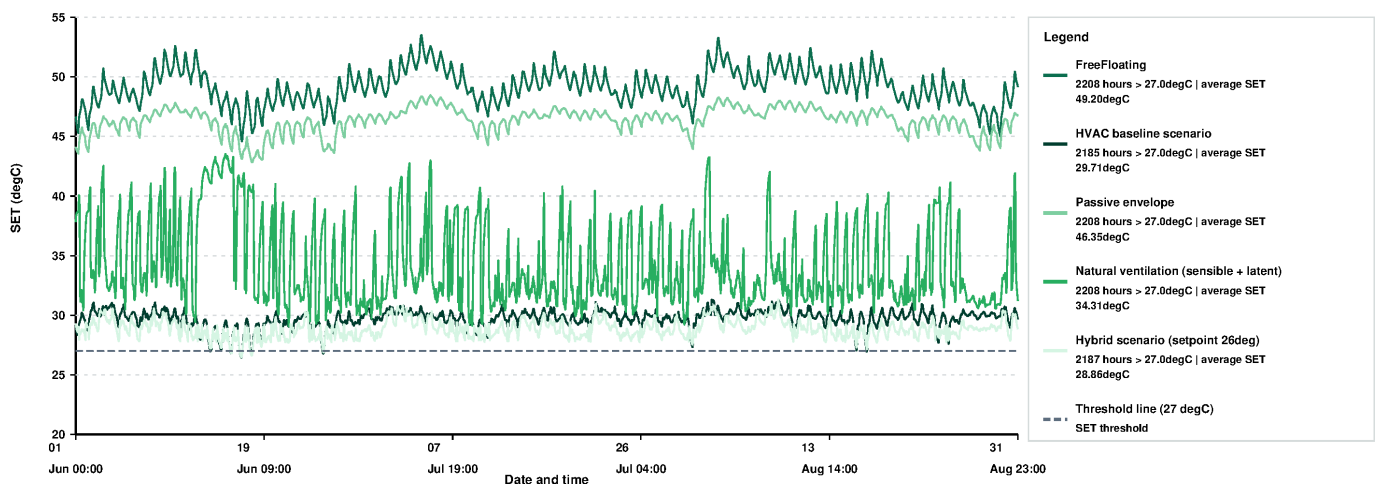


Fig. N.8.2: Comparison hourly SET for all scenarios (Bedridden patient)

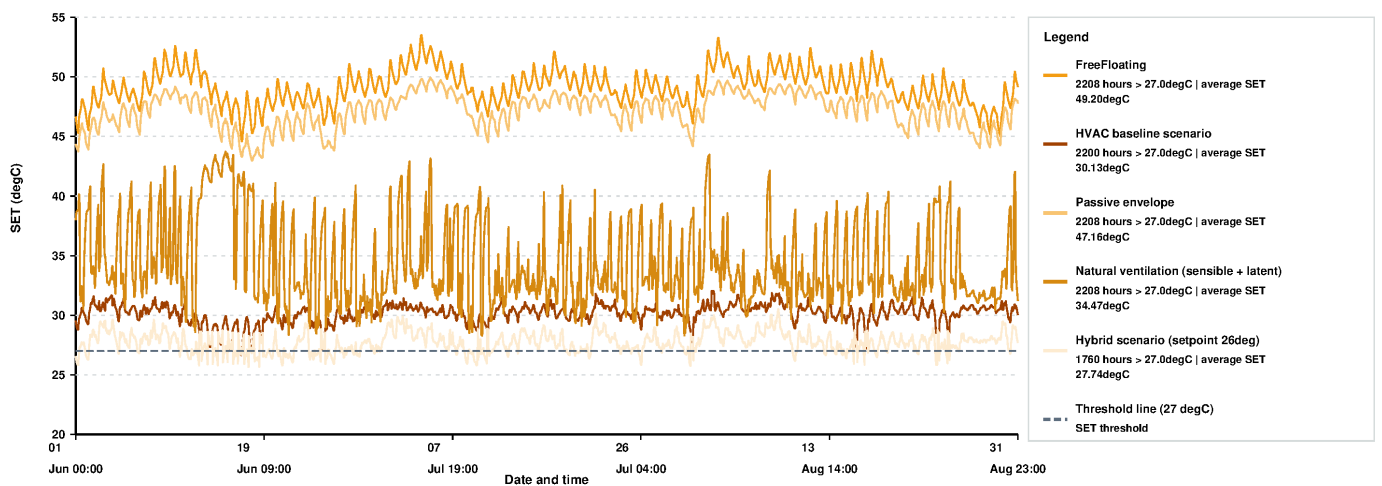


Fig. N.8.3: Comparison hourly SET for all scenarios (Staff)

N.9 Hourly SET/ T_o for all scenarios mobile patient

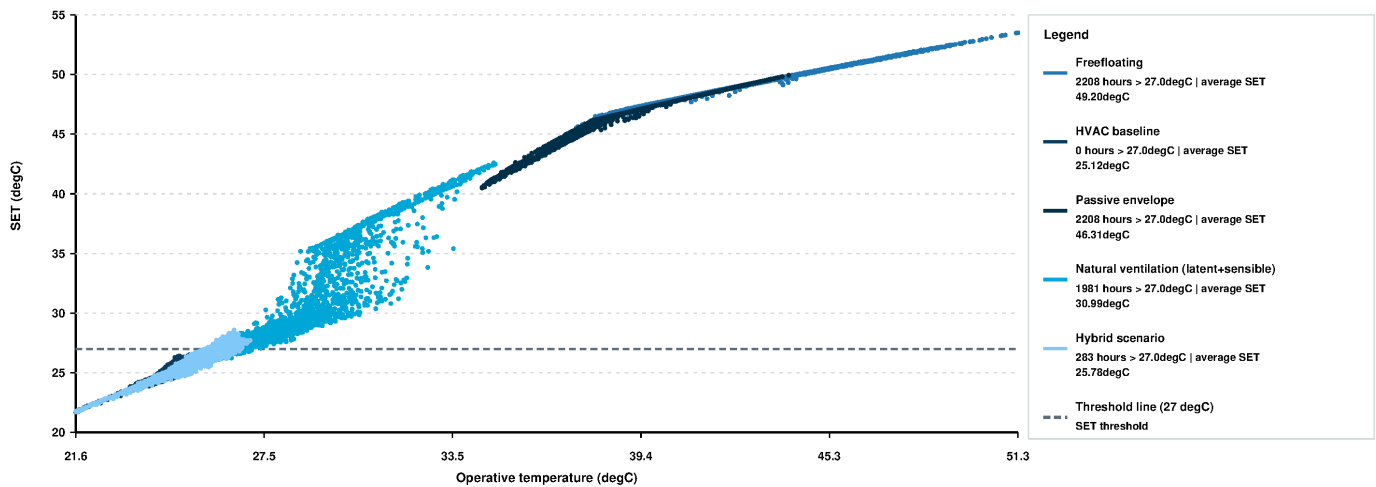


Fig. N.9.1: Hourly SET/ T_o for all scenarios mobile patient

N.10 Scenario summary

Scenario summary

Average operative temperature, SET, PPD, and overheating metrics for each scenario

Scenario	User group	avg T_o	min T_o	max T_o	avg SET	min SET	max SET	avg PPD	Hours SET > 27
FreeFloating	Mobile	42.9 degC	36.8 degC	51.3 degC	49.2 degC	44.6 degC	53.5 degC	100.0%	2208
HVAC baseline	Mobile	24.6 degC	21.6 degC	26.3 degC	25.1 degC	21.7 degC	26.9 degC	6.0%	0
HVAC baseline	Bedridden	24.6 degC	21.6 degC	26.3 degC	29.7 degC	26.5 degC	31.3 degC	18.3%	2185
HVAC baseline	Staff	24.6 degC	21.6 degC	26.3 degC	30.1 degC	26.7 degC	32.0 degC	23.5%	2200
Passive env.	Mobile	38.9 degC	34.4 degC	44.1 degC	46.3 degC	40.5 degC	49.9 degC	100.0%	2208
Passive env.	Bedridden	38.9 degC	34.4 degC	44.1 degC	46.4 degC	42.8 degC	48.5 degC	100.0%	2208
Passive env.	Staff	38.9 degC	34.4 degC	44.1 degC	47.2 degC	43.0 degC	49.9 degC	100.0%	2208
NV sens. + lat.	Mobile	28.8 degC	25.3 degC	34.8 degC	30.1 degC	22.7 degC	42.6 degC	38.9%	1478
NV sens. + lat.	Bedridden	28.8 degC	25.3 degC	34.8 degC	34.3 degC	29.1 degC	43.5 degC	63.8%	2208
NV sens. + lat.	Staff	28.8 degC	25.3 degC	34.8 degC	34.5 degC	28.3 degC	43.7 degC	61.9%	2208
Hybrid operation	Mobile	25.2 degC	21.6 degC	27.1 degC	25.8 degC	21.7 degC	28.6 degC	7.6%	283
Hybrid operation	Bedridden	25.2 degC	21.6 degC	27.1 degC	28.9 degC	26.5 degC	31.3 degC	12.5%	2187
Hybrid operation	Staff	25.2 degC	21.6 degC	27.1 degC	27.7 degC	25.7 degC	30.5 degC	9.8%	1760

Fig. N.10.1: Summary of scenario results for all user groups

O Interview protocol

Interview phase	Approx. duration	Aim	Topics / activities	Output
1. Introduction	3 min	Introduce the research context and interview purpose	Brief explanation of the thesis topic, passive cooling focus, anonymisation, consent and recording procedure	Shared understanding of interview scope
2. Respondent background	3 min	Understand the respondent's role and expertise	Professional role, project involvement, experience with healthcare buildings, passive design or indoor climate	Context for interpreting responses
3. Semi-structured interview	20 min	Explore current practice and implementation conditions	Current cooling and ventilation practice; role of passive strategies; thermal comfort approach; user differentiation; natural ventilation; design-process conditions; stakeholder roles; risk, regulation and decision-making	Qualitative insight into practical barriers, drivers and design-process conditions
4. Card-ranking exercise: barriers	10 min	Identify perceived importance of implementation barriers	Respondents ranked predefined barrier cards from most to least important. Participants were asked to think aloud while ranking and could add missing barriers	Indicative ranking of barriers + qualitative reasoning
5. Card-ranking exercise: drivers	10 min	Identify perceived importance of enabling conditions	Respondents ranked predefined driver cards from most to least important. Participants were asked to think aloud while ranking and could add missing drivers	Indicative ranking of drivers + qualitative reasoning
6. Reflection and closing	5 min	Capture final remarks and validate key points	Open reflection on missing themes, most important takeaway, possible recommendations for practice	Additional insights and final clarification

Table O.1: Simplified interview set-up

Theme	Focus
Current cooling and ventilation practice	How are cooling and ventilation strategies currently developed in healthcare buildings?
Knowledge and experience with passive cooling	How familiar are stakeholders with passive design principles, and where are they already applied?
Thermal comfort	How is comfort defined, assessed and monitored, and to what extent are user differences considered?
Natural ventilation and air movement	Under which conditions are openable windows, natural ventilation or increased air speed considered feasible?
User differentiation	How are different user groups, such as patients, staff and vulnerable occupants, addressed in comfort strategies?
Risk and reliability	How are uncertainty, infection prevention, air quality, system control and operational reliability considered?
Design process and stakeholder roles	When are key decisions made, which stakeholders influence them, and where do passive strategies lose or gain support?
Implementation barriers and drivers	What prevents or supports the implementation of passive cooling in healthcare design practice?
Design and simulation implications	What evidence is needed to make passive strategies credible and useful in early-stage design?

Table O.2: Example questions interview part 1.

Eigenaarschap & verantwoordelijkheid <i>"Het is onduidelijk wie eigenaar is van passieve concepten en wie hiervoor verantwoordelijk is."</i>	Een opdrachtgever met een duidelijke duurzaamheidsambitie maakt echt verschil.
Controle en zekerheid <i>"Installaties voelen betrouwbaarder en beter te controleren dan passieve oplossingen"</i>	Praktische richtlijnen en prestatie benchmarks geven houvast in het ontwerp.
PVE <i>"Het PVE is helemaal dichtgetimmerd met Eisen gerelateerd gericht op mechanische koeling, er is geen oplossing vrijheid meer."</i>	Regelgeving of beleid kan innovatie richting passieve koeling stimuleren.
Kennis <i>"Er is te weinig kennis van passieve maatregelen."</i>	Eerder betrekken van bouwfysica- en comfortexperts helpt in het formuleren van de ambities.
Kosten <i>"De perceptie is er dat passieve koeling duurder is dan conventionele systemen"</i>	Beter kennis deling over passief ontwerpen verbreed het draagvlak.
Timing in ontwerpproces <i>"De juiste expertise over passief koelen wordt pas laat betrokken, wanneer de meeste ontwerp vrijheid weg is."</i>	Meer integrale samenwerking tussen stakeholders is nodig om alle partijen in dezelfde richting te krijgen.
Systeem <i>"Het ontwerpproces gaat al jaren via dezelfde werkwijze, verandering in het systeem is moeilijk"</i>	Met meer bewustwording van toenemende hitte en klimaat risico's worden andere ontwerpkeuzes gestimuleerd
Bewijs en tastbaarheid <i>"Er zijn te weinig richtlijnen of bewijs dat passieve koeling werkt. Het wordt ervaren als vaag"</i>	Als faalkosten en risico's van installaties expliciet worden meegenomen, wordt passief ontwerpen aantrekkelijker.
Dominantie stakeholders <i>"Er is onvoldoende overtuigingskracht of interesse vanuit diverse stakeholders"</i>	Als er duidelijke interne trekkers of ambassadeurs zijn voor passief ontwerpen, komt het sneller van de grond.
Wet- en regelgeving <i>"Door huidige wet en regelgeving is het niet mogelijk om passieve koeling toe te passen"</i>	Als comfort- en prestatie-eisen anders worden geformuleerd in PVE , ontstaat meer ontwerp vrijheid.
Extra:	Extra:
Extra:	Extra:

Fig. O.1: Ranking cards for barriers and drivers used in the interviews.

P. Data management plan and ethics

ABE MSc BT Graduation Project - Lieke Buijssen - Interview data

0. Administrative questions

The DMP has been shared with my thesis supervisor Alessandra Luna Navarro and Atze Boerstra via DMPonline, and Alessandra reviewed it on 24-2-2026 and 18/3/2026. The Data steward did quick review since this is low-risk it doesn't need review from data steward.

- Yes, leading the collaboration – please provide details of the type of collaboration and the involved parties below

The MSc graduation project is conducted as part of a graduation internship at Deerns Nederland, within the building physics and Energy team. Only the final thesis report will be shared with the company as it is in the public repository of tu Delft.

I. Data/code description and collection or re-use

Type of data/code	File format(s)	How will data/code be collected/generated? <i>For re-used data/code: what are the sources and terms of use?</i>	Purpose of processing	Storage location	Who will have access to the data/code?
Personally Identifiable Information (PII): participants' name, email, work address, company name, mobile	.xlsx	Contact information for participants taking part in interviews, received from professional network Informed consent forms are signed digitally and contain participants' name + email.	For administrative purposes: obtaining informed consent and communicating with participants	TU Delft One drive	Lieke Buijssen (master student) + Atze Boerstra + Alessandra Luna Navarro
Signed consent forms	hard copy			TU Delft One drive	same as above
Audio recordings from interview with experts in the building physics field	.mp3	Interviews are conducted during on-site visits or online. Audio- recordings are made on an external device, before being moved to project folder recordings are deleted after transcription.	Capturing experts opinion on implementation barriers of passive cooling in healthcare buildings.	Temporarily stored on recording device (TEAMS). transcription afterwards stored TU Delft One drive	same as above
Anonymous transcriptions of interviews	.docx	Anonymous transcriptions created manually based on audio- recordings.	understanding user opinion passive cooling in healthcare buildings	TU Delft One Drive	same as above

II. Storage and backup during the research process

- < 250 GB
- TU Delft OneDrive

III. Data/code documentation

- Data – Methodology of data collection

IV. Legal and ethical requirements, code of conducts

- Yes – please provide details in the additional information box below

We are applying for HREC

- Yes

Yes only for administrative purposes consent forms and organizing the interview. the interview transcripts are anonymized, the recordings are deleted as soon as the anonymized transcripts are ready.

- No, I will not work with any other types of confidential or classified data/code

The intellectual property rights are framed by a graduation agreement between Delft University of Technology, myself and Deerns Nederland

- Proof of consent (such as signed consent materials which contain name and signature)
- Audio recordings
- Job title and/or employer
- Telephone number, email addresses and/or other addresses as contact details for administrative purposes
- Names as contact details for administrative purposes

Personally Identifiable Information (PII): interviewee name, work address, company name, email address are processed for administrative reasons (to obtain informed consent and communicate with participants).

And the consent forms as well.

Personally Identifiable Research Data (PIRD): Personal research data processed for interview participants includes:

- audio-recordings

Participant data for interviewees is anonymised when recordings are transcribed

Interview participants are residents in the Netherlands and work in the field of building physics or healthcare related built environment.

- No
- Informed consent

8. APPENDICES

I will prepare the form of consent form as for TU Delft template and ask for reading, and signature

in a locked cabinet in TU Delft Bouwkunde

- None of the above apply
- Anonymised or aggregated data will be shared with others
- Other – please state the duration and explain the rationale below

For the duration of the project (half june)+ 1 month (for clean up)

- In the informed consent form: participants are informed that their personal data will be anonymised and that the anonymised dataset is shared publicly

V. Data sharing and long term preservation

- All other non-personal data/code underlying published articles/reports/theses
- I am a Bachelor's/Master's student at TU Delft and I will share the data/code in the body and/or appendices of my thesis/report in the TU Delft Repository
- < 100 GB

- As soon as corresponding results (papers, theses, reports) are published

Anonymised data collected during the project will be included in the body and appendix of the MSc thesis, made available in the TU Delft Repository.

- CC BY

The thesis is made publicly available in the TU Delft Repository

VI. Data management responsibilities and resources

My supervisors Prof.dr.ir. A.C. Boerstra architectural engineering & technology) and Dr. A. Luna Navarro (architectural engineering & technology).

Research data are only shared within the MSc thesis: no additional resources are required

- Faculty of Architecture and the Built Environment (ABE)

Q. Interview quotes

Original Dutch quotes

“betrokken na PVE, daar zijn klimaateisen in over hoeveel mensen ze verwachten, hoeveel apparatuur en hoeveel interne warmelasten etc. en dat is waar we gewoon beginnen. (I)”

“Je ziet wel dat de zon bijdraagt. Het voelt veel, maar als je ziet hoeveel apparatuur er binnen wordt gesleept bij sommige patiënt kamers, dan is het maar een kwart.”

“Wij willen ook het liefst eerst passief bouwen maar je begint altijd wel een beetje te rekenen zonder passief. Je begint altijd een beetje worstcase. Kan je dat dan nog in een gebouw kwijt. En als je in een fase zit waarin je ruimte moet kleven bij een architect. Dan moet dat je uitgangspunt zijn.”

“Je ziet in de gezondheidszorg de passieve benadering juist teruglopen”

“te openen ramen de installaties verstoren”

“Wat je dus wil voorkomen is dat je aan de ene kant vanuit beleving zegt, dat raampunt willen we open kunnen, maar je bent met je plafond of ander systeem ook direct weer aan het koelen. Dan ben je natuurlijk energetisch water naar de zee aan het dragen en dat willen we eigenlijk ook niet. Wat je dus moet voorkomen, zeker in een 24-7 gebruik van het gebouw, is dat je dit soort aspecten krijgt, want dan krijg je op s'nachts ook niet meer weggekoeld.”

“En dan zie je eigenlijk dat die laatste periode van 2025 mensen het meest gewend waren aan de warmte. Dus een ruimtetemperatuur als koeler beoordeelde dan aan het begin van de zomer, maar ook als in 2024.”

“Om heel eerlijk te zijn, dat we vanuit installatietechniek er nog niet voldoende mee bezig zijn, daar ontbreekt nog kennis.”

“Het gevaar van klachtensysteem is dat mensen ook klachten gaan melden wat er eigenlijk geen klacht is. Want als het 24 graden is en ik vind het niet lekker, ga ik het melden als klacht. Maar het systeem zegt dat het gewoon goed is natuurlijk. Ja.”

“ik ben bang dat het een knip en piepsysteem. Oftewel als er niet gepiept wordt dan is het goed.”

English translation used in the thesis report

“involved after the PVE, which includes climate requirements regarding the number of people they expect, the amount of equipment, and the internal heat loads, etc., and that is simply where we start. (I)”

“The sun may feel like a major heat source, but when you see how much equipment is brought into some patient rooms, it only accounts for about a quarter.”

“Ideally, we would also prefer to start with passive design. However, in practice, calculations often begin without accounting for passive measures, using a kind of worst-case scenario. The question then becomes whether the required installation capacity can still be accommodated in the building. Especially in a phase where technical space has to be negotiated with the architect, that worst-case scenario becomes the starting point.”

“In healthcare, the passive approach actually seems to be declining.”

“operable windows disrupt building services systems”

“What you want to avoid is a situation where, from a user-experience perspective, you want a window to be openable, while at the same time the ceiling system or another system is actively cooling the room. From an energy perspective, that is simply wasteful. Especially in a building that operates 24/7, you want to prevent this kind of conflict, because it can also prevent the building from cooling down again at night.”

“You can see that in the later period of 2025, people were most accustomed to the heat. As a result, a room temperature was perceived as cooler than at the beginning of the summer, and also compared to 2024.”

“From a building services perspective we are not sufficiently engaged with this yet; there is still a lack of knowledge.”

“The risk of a complaint-based system is that people may start reporting issues that are not actually technical problems. If the room is 24 degrees and I personally do not find it comfortable, I may report it as a complaint, while the system indicates that the conditions are within the required range.”

“I am afraid it becomes a ‘squeak and complain’ system, meaning that if no one complains, it is considered acceptable.”

Original Dutch quotes

“Om niet in de valkuil te stappen. Maar als Erasmus doen we het al jaren zo. Dus we willen ook SPOT op die manier. Dat kan. Alleen techniek gaat verder. Het gebouw is anders. Het gebouw is misschien net weer wat anders in gebruik. Dadelijk dan een centrumlocatie.”

“In de bouw zijn het allemaal schakeltjes, iedereen is verantwoordelijk voor een deel, controle en zekerheid is altijd wel belangrijk in de bouw.”

“Iedereen wil het zelfde, met dezelfde ambitie, maar je ziet allerlei verschillende eisen en waarden voorkomen. En in de pve staan er allerlei eisen die feitelijk hetzelfde zeggen. Maar net anders geïnterpreteerd zijn. Of anders zijn opgeschreven. Maar feitelijk met hetzelfde doel.”

“Soms worden ze pas ingeschakeld als er een probleem is.”

“Soms moet je opdrachtgevers of stakeholder een stip op de horizon laten zien, mensen redeneren toch en dat is heel menselijk vanuit het hier en nu en van hoe het nu is, hoe ze nu werken en hoe ze het nu ervaren. Maar onze taak is ook om ze te laten zien hoe het zou kunnen zijn in de toekomst.”

“Maar zolang je het nog kan fixen. Met de installatietechniek. Heb je inderdaad als installatiebeleider. Een minder zware stem dan architect. Ja dat wordt geheel veel mooier gemaakt.”

“Voor ziekenhuis wordt zo generiek mogelijk ontworpen, Dus mediumcare en highcare is nagenoeg hetzelfde, IC hebben we, maar dat is een zelfstandige eenheid en isolatiekamers.”

“het moet een keer misgaan om bij mensen de urgentie aan te wakkeren.”

“zorginstellingen hebben vaak gewoon beperkte middelen om in vastgoed te investeren. Dus er wordt heel kostengedreven gedacht. Maar dan ook kostengedreven op de korte termijn.”

“Ja, gefixeerde zonwering, dan wordt dat dan een bouwkundig element. Dus dat is dan een kostenplus waar je eigenlijk niks voor terugkrijgt op de korte termijn, wat je terugverdiend is moeilijk te waarderen.”

“Dan kan je rekenen maar even voor de vuistweg, tussen de 3.000 en 3.200 euro de vierkante meter voor een ziekenhuis.

English translation used in the thesis report

“The pitfall is to say: At Erasmus, we have always done it this way, so we want SPOT to be designed in the same way.’ That may be possible, but technology is developing, the building is different, and its use may also differ from the existing central location.”

“In construction, everything consists of many interconnected links. Each party is responsible for one part of the process, and control and certainty are always important.”

“Everyone is aiming for the same ambition, but in practice you see many different requirements and values appear. The Programme of Requirements often contains requirements that essentially express the same objective, but are interpreted or written down slightly differently.”

“Sometimes they are only involved when a problem occurs.”

“Sometimes you have to show clients or stakeholders a point on the horizon; people reason from the here and now, from how things are and how they currently work and experience them. But our task is also to show how it could be in the future.”

“As long as the issue can still be solved through building services, the installation advisor has less influence than the architect. Architectural arguments are often given more weight.”

“Hospitals are designed as generically as possible. Medium care and high care are therefore almost the same, while ICUs and isolation rooms are treated as separate units.”

“Something has to go wrong to create a sense of urgency.”

“Healthcare institutions often simply have limited resources to invest in real estate. As a result, decision-making is highly cost-driven, particularly focused on the short term.”

“With fixed solar shading, it becomes an architectural element. That means it is seen as an additional cost, while the short-term return is difficult to quantify.”

“As a rough estimate, the construction cost of a hospital is around €3,000 to €3,200 per square metre. Depending on the project,

Original Dutch quotes

En dan is het aandeel techniek zo'n 15, 50, 1.600 afhankelijk van."

"Wij worden geacht TCO-berekeningen te maken. Wat je helaas ziet is dat dat dan alleen gebruikt wordt voor de intrinsieke investeringsmaatregelen. Wat je dus ziet is dat het niet vanuit beheersmaatregelen je budgetverhoging toegekend krijgt."

"Als het niet in regelgeving niet opgenomen is dan wordt het toch moeilijker en valt het uiteindelijk wel als eerste af."

"Over te openen ramen krijg je altijd discussies met de gebouwbeheerders, die zeggen dat het de luchtdruk frustreert."

"we zijn de controle over onze eigen gebouwen verloren, alles is geoutsourced en zo complex geworden dat we ze vanuit garantieoverwegingen niet eens mogen aanraken."

"Bij SPOT heb je met zoveel andere randvoorwaarden stedenbouwkundige plannen te maken. De gemeente Rotterdam die meekijkt. De gemeente heeft een bepaald idee bij de gevel. Dat maakt wel dat in de hoek wordt geduwd."

"We hebben buitenlucht het liefst gewoon buiten."

"Ik denk dat eigenaarschap en verantwoordelijkheid, daar start alles bij. Als je iemand hebt die dat niet heeft, of een opdrachtgever die dat niet heeft, of die daar ook geen belang in heeft. Dan kun je praten als brugman of dan kun je van alles willen maar dan gebeurt er gewoon niks."

"Je moet accepteren dat je ook geen 100% flexibiliteit hebt in indelen van ruimte. Er zit een bepaalde logica in, een bepaalde luchtdoorstroming. Met die beperkingen moet je ook meegaan."

"installatiemonsters"

"Ventilator kan een goeie aanvulling zijn om het thermisch comfort te verbeteren, maar we moeten wel de gebruikers daar wel aan gaan laten wennen."

"Een bedventilator zou een goeie lokale oplossing zijn voor bedliggende patiënten. Daarbij is het niet erg als er een kans op tocht ontstaat omdat mensen deze dan zelf kunnen aanpassen aan de situatie."

"je moet niet te veel blind staren op wat voor een range aan patiënten er zijn. Maar behalve dat je eigenlijk wel zeker weet dat die range heel breed gaat zijn en dat het dus een oplossing moet zijn wat voor iedereen aanpasbaar is."

English translation used in the thesis report

the share of building services can be around €1,500 to €1,600 per square metre."

"We are expected to carry out TCO calculations. However, in practice these are often only used to assess direct investment measures. What you see is that operational or management-related savings do not necessarily lead to an increased upfront budget."

"If it is not included in regulations, it becomes more difficult and is often the first to be discarded."

"Discussions about operable windows always arise with facility managers, who argue that it disrupts air pressure."

"We have lost control over our own buildings; everything is outsourced and has become so complex that we are not even allowed to touch them due to warranty considerations."

"In SPOT, there are many additional constraints related to the urban design plan. The Municipality of Rotterdam is involved and has a specific vision for the façade. This does push the design in a certain direction."

"We prefer to keep outdoor air outside."

"Ownership and responsibility is where it all starts. If you have someone who does not have that, or a client who does not have it or does not value it, then no matter how much you argue or try, nothing will happen."

"You have to accept that you do not have complete freedom in spatial layout; there is an inherent logic and airflow structure that must be accommodated."

"installation-monsters"

"A fan can be a good addition to improve thermal comfort, but users need to get accustomed to it."

"A bed fan could be a good local solution for bedridden patients. In that case, it is not problematic if there is a risk of draught, as users can adjust it themselves."

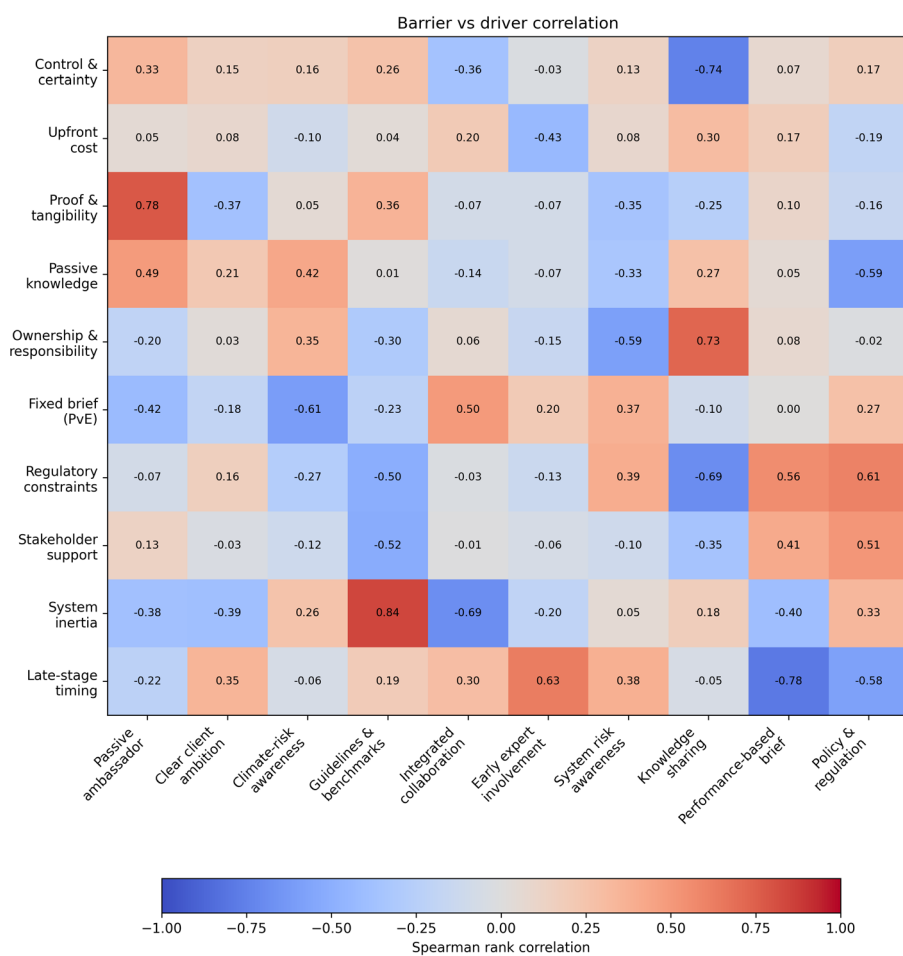
"One should not focus too narrowly on defining a specific patient range; rather, it is clear that this range is very broad, meaning solutions should be adaptable to individual needs."

R. Quantitative interview results

(H1)			(A1)			(A2)		
	Barriers	Drivers		Barriers	Drivers		Barriers	Drivers
High 10	Knowledge	Ambition	High 10	Ownership	Ambition	High 10	PVE	Ambition
	9 Control & uncertainty	Ambassador		9 Costs	Knowledge		9 Regulationss	Regulationss
	8 Ownership	Experts		8 Knowledge	Cooperation		8 Control & uncertainty	PVE
	7 Evidence	Cooperation		7 Timing	Experts		7 Stakeholders	Experts
	6 Stakeholders	Awareness		6 Control & uncertainty	Ambassador		6 Ownership	Installation failures
	5 Costs	PVE		5 Stakeholders	Awareness		5 Costs	Cooperation
	4 Timing	Installation failures		4 PVE	benchmarks		4 Timing	Knowledge
	3 PVE	Knowledge		3 System	Regulationss		3 System	Ambassador
	2 Regulationss	benchmarks		2 Evidence	Installation failures		2 Evidence	benchmarks
	1 System	Regulationss		1 Regulationss	PVE		1 Knowledge	Awareness
(C2)			(T1)			(T2)		
	Barriers	Drivers		Barriers	Drivers		Barriers	Drivers
High 10	Ownership	Regulationss	High 10	Timing	Experts	High 10	Stakeholders	Cooperation
	9 System	benchmarks		9 System	benchmarks		9 Control & uncertainty	Ambassador
	8 Control & uncertainty	Knowledge		8 Costs	Ambition		8 PVE	Experts
	7 Stakeholders	Awareness		7 Control & uncertainty	Installation failures		7 Evidence	Ambition
	6 Evidence	Ambition		6 PVE	Knowledge		6 Regulationss	Regulationss
	5 PVE	Ambassador		5 Knowledge	Cooperation		5 Timing	Installation failures
	4 Costs	PVE		4 Evidence	Ambassador		4 Costs	PVE
	3 Knowledge	Experts		3 Stakeholders	Awareness		3 System	benchmarks
	2 Regulationss	Cooperation		2 Ownership	Regulationss		2 Knowledge	Awareness
	1 Timing	Installation failures		1 Regulationss	PVE		1 Ownership	Knowledge
(I1)			(B1)			(A3)		
	Barriers	Drivers		Barriers	Drivers		Barriers	Drivers
High 10	Costs	Knowledge	High 10	Control & uncertainty	benchmarks	High 10	Knowledge	PVE
	9 Ownership	Ambassador		9 Evidence	Ambassador		9 Costs	Ambassador
	8 PVE	Cooperation		8 System	Ambition		8 Control & uncertainty	Ambition
	7 Evidence	PVE		7 Knowledge	Experts		7 Stakeholders	Regulationss
	6 Control & uncertainty	benchmarks		6 Timing	Knowledge		6 Evidence	benchmarks
	5 Knowledge	Regulationss		5 Stakeholders	Regulationss		5 Ownership	Knowledge
	4 Stakeholders	Ambition		4 Costs	PVE		4 System	Installation failures
	3 System	Experts		3 PVE	Awareness		3 Regulationss	Awareness
	2 Timing	Awareness		2 Ownership	Cooperation		2 PVE	Cooperation
	1 Regulationss	Installation failures		1 Regulationss	Installation failures		1 Timing	Experts
(A4)								
	Barriers	Drivers						
High 10	Control & uncertainty	benchmarks						
	9 Costs	Ambition						
	8 System	Ambassador						
	7 Evidence	Regulationss						
	6 PVE	Installation failures						
	5 Timing	Awareness						
	4 Stakeholders	PVE						
	3 Knowledge	Cooperation						
	2 Regulationss	Experts						
	1 Ownership	Knowledge						

Note. I1 indicated that installation failure and awareness of increasing heat were considered less relevant and effectively fell outside the final list. A4 suggested adding a supplementary barrier related to evidence, namely that the benefits of the healing environment are still insufficiently substantiated.

S. Spearman rank correlation between barriers and drivers



8. APPENDICES

T. Passive-first dialogue starter cards

PASSIVE-FIRST HEALTHCARE BUILDINGS		TOWARDS PASSIVE-FIRST HEALTHCARE BUILDINGS		WHO IS RESPONSIBLE FOR PROTECTING PASSIVE AMBITIONS DURING BUDGET OR PLANNING PRESSURE?		DOES THE PVE DISTINGUISH BETWEEN AMBITIONS, PERFORMANCE GOALS AND FIXED TECHNICAL REQUIREMENTS?		WILL THE PROJECT FOLLOW A PASSIVE-FIRST METHODOLOGY OR AN INSTALLATION-FIRST METHODOLOGY?	
PASSIVE-FIRST HEALTHCARE BUILDINGS		TOWARDS PASSIVE-FIRST HEALTHCARE BUILDINGS		WHO IS RESPONSIBLE FOR PROTECTING PASSIVE AMBITIONS DURING BUDGET OR PLANNING PRESSURE?		DOES THE PVE DISTINGUISH BETWEEN AMBITIONS, PERFORMANCE GOALS AND FIXED TECHNICAL REQUIREMENTS?		WILL THE PROJECT FOLLOW A PASSIVE-FIRST METHODOLOGY OR AN INSTALLATION-FIRST METHODOLOGY?	
PASSIVE-FIRST HEALTHCARE BUILDINGS		TOWARDS PASSIVE-FIRST HEALTHCARE BUILDINGS		WHO IS RESPONSIBLE FOR PROTECTING PASSIVE AMBITIONS DURING BUDGET OR PLANNING PRESSURE?		DOES THE PVE DISTINGUISH BETWEEN AMBITIONS, PERFORMANCE GOALS AND FIXED TECHNICAL REQUIREMENTS?		WILL THE PROJECT FOLLOW A PASSIVE-FIRST METHODOLOGY OR AN INSTALLATION-FIRST METHODOLOGY?	
ARCHITECT CARD 01 CAN AIR MOVEMENT BE ACTIVELY USED AS A STRATEGY TO IMPROVE COMFORT IN PATIENT ROOMS? Fact Increasing air velocity enhances heat loss from the human body, allowing higher indoor temperatures while maintaining comfort. Design implications - Integration of ceiling fans - Increased ceiling height - Air supply near patient zone Programme implications - Define acceptable air velocity - Allow local control systems - Include adaptive comfort criteria	ARCHITECT CARD 02 WHICH PASSIVE OPPORTUNITIES ARE ALREADY CONSTRAINED BY URBAN OR FAÇADE REQUIREMENTS? Fact Passive cooling potential is strongly affected by early decisions on orientation, façade and massing. Design implications - Evaluate climate impact before fixing façade concepts - Test multiple massing options early - Align municipality and climate ambitions from the start	ARCHITECT CARD 03 IS EXTERNAL SHADING TREATED AS AN INTEGRAL FAÇADE ELEMENT OR AS A TECHNICAL ADD-ON? Fact Solar gains are one of the few thermal loads that can be effectively reduced before entering the building. Design implications - Integrate shading within the façade concept from the start - Differentiate shading by orientation and room type - Establish daylight quality with overheating prevention	INSTALLATION EXPERT CARD 16 SHOULD PASSIVE POTENTIAL BE EXPLORED BEFORE DEFINING INSTALLATION CAPACITY? Fact Current hospital design often starts from worst-case mechanical capacity assumptions. Programme implications - Define passive potential before system sizing - Delay fixing HVAC capacity in early phases - Include passive-first studies within the SO phase	INSTALLATION EXPERT CARD 17 SHOULD INDOOR CLIMATE CONTROL REMAIN FULLY CENTRALISED? Fact Users highly value personal control over their indoor environment, even when measurable conditions remain unchanged. Design implications - Combine central reliability with local adaptability - Integrate controllable airflow or temperature zones - Evaluate operational boundaries for user control	INSTALLATION EXPERT CARD 18 HOW CAN MECHANICAL AND NATURAL VENTILATION SUPPORT EACH OTHER INSTEAD OF COMPETING? Fact Operable windows and passive airflow often conflict with mechanical cooling when no integrated control logic is defined. Design implications - Define when natural ventilation is allowed or blocked - Coordinate façade operation with HVAC control systems - Use performance ambitions instead of predefined systems in the PVE				
USER / HEALING ENVIRONMENT CARD 04 TO WHAT EXTENT SHOULD PATIENTS OR STAFF BE ABLE TO INFLUENCE THEIR LOCAL INDOOR CLIMATE? Fact Perceived control over the indoor environment significantly improves thermal satisfaction, even when physical conditions remain unchanged. In addition, enabling adaptive actions (e.g. adjusting airflow, temp. or shading) allows occupants to tolerate a wider temperature range. Design implications - Integrate operable elements (windows, shading devices) - Allow local air movement (e.g. fans, directional airflow) - Design zones with different thermal conditions - Position controls within reach of users or staff Programme implications - Define levels of user control - Include adaptive comfort criteria - Specify provisions for local environmental adjustment - Align control strategies with infection control and safety requirements	USER / HEALING ENVIRONMENT CARD 05 CAN ONE THERMAL ENVIRONMENT SATISFY ALL USERS EQUALLY? Fact Thermal comfort differs strongly between patients, staff and visitors. Design implications - Differentiate comfort strategies by room type - Allow variation in thermal conditions across spaces - Avoid uniform climate assumptions for all users - Balance generic design for future flexibility with differentiated thermal zones	USER / HEALING ENVIRONMENT CARD 06 CAN NATURAL VENTILATION BE APPLIED SELECTIVELY WITHOUT COMPROMISING INFECTION CONTROL? Fact Infection prevention is often the decisive factor in rejecting natural ventilation concepts in hospitals. Design implications - Differentiate between high-risk and low-risk ventilation zones - Evaluate natural ventilation in outpatient or office-like functions - Test airflow containment and pressure relationships explicitly	PROJECT MANAGER CARD 19 ARE THE RIGHT EXPERTS INVOLVED BEFORE KEY SPATIAL AND TECHNICAL DECISIONS ARE FIXED? Fact Building physics and installation experts are often involved after major assumptions in the PVE and layout are already defined. Process implications - Involve climate expertise during intuitive and schematic design phases - Align technical and spatial decisions early - Prevent passive measures from becoming post-rationalisations	PROJECT MANAGER CARD 20 ARE PASSIVE DESIGN DECISIONS EVALUATED ACROSS DISCIPLINES OR WITHIN SEPARATE SCOPES? Fact Are passive design decisions evaluated across disciplines or within separate scopes? Process implications - Organise interdisciplinary climate workshops early - Integrate façade, comfort and HVAC strategies together - Define shared project ambitions across stakeholders	PROJECT MANAGER CARD 21 WHAT LEVEL OF EVIDENCE IS REQUIRED BEFORE PASSIVE STRATEGIES BECOME ACCEPTABLE? Fact Passive concepts require strong simulation evidence and reference projects to influence healthcare decisions. Process implications - Integrate simulations into early decision-making - Compare passive and active scenarios explicitly - Use evidence to support strategic design decisions				
BUILDING PHYSICIST CARD 07 ARE CLIMATE SIMULATIONS USED TO GUIDE DESIGN OR ONLY TO VERIFY COMPLIANCE? Fact Late-stage simulations limit meaningful passive design adjustments. Programme implications - Start overheating studies during concept design - Use simulations to compare passive strategies early - Include scenario-based evaluation instead of single-value checks	BUILDING PHYSICIST CARD 08 IS THE DESIGN TESTED AGAINST FUTURE HEATWAVES AND UNCERTAINTY SCENARIOS? Fact Climate change increases overheating risk and cooling dependency in healthcare buildings. Programme implications - Simulate future climate scenarios explicitly - Use future projected weather data - Evaluate worst-case and adaptive scenarios - Include resilience criteria in performance targets	BUILDING PHYSICIST CARD 09 CAN WE REDUCE INTERNAL HEAT GAINS FROM EQUIPMENT OR LIGHTING? Fact In patient rooms, internal heat gains from equipment, lighting and occupancy can outweigh solar gains and reduce passive cooling potential. Programme implications - Reduce unnecessary equipment loads - Optimise lighting in patient rooms - Integrate low-heat lighting strategies early in the design - Separate high-load equipment zones from sensitive comfort areas	CLINICAL SAFETY CARD 22 CAN NATURAL VENTILATION BE APPLIED WITHOUT COMPROMISING INFECTION PREVENTION? Fact Infection prevention was repeatedly identified as a decisive barrier to passive ventilation strategies. Design implications - Differentiate ventilation strategies by risk profile - Align natural ventilation selectively in low-risk areas - Integrate infection prevention early in passive design discussions	CLINICAL SAFETY CARD 23 WHEN DOES BENEFICIAL AIR MOVEMENT BECOME A CLINICAL RISK? Fact Local airflow may improve comfort but raises concerns regarding airflow mixing and contaminant transport. Design implications - Assess airflow containment alongside comfort - Evaluate patient-controlled airflow concepts carefully - Differentiate comfort airflow from critical airflow zones	CLINICAL SAFETY CARD 24 SHOULD ALL HOSPITAL SPACES FOLLOW THE SAME INFECTION-CONTROL VENTILATION STRATEGY? Fact Highly controlled spaces often determine the climate strategy for entire hospital zones. Process implications - Separate high-risk and low-risk ventilation concepts - Avoid applying ICU logic to all patient areas - Define passive potential per healthcare function				
COST EXPERT CARD 10 SHOULD PASSIVE CLIMATE STRATEGIES BE EVALUATED AS ARCHITECTURAL COSTS, ENGINEERING COSTS, OR LONG-TERM OPERATIONAL INVESTMENTS? Fact Passive strategies are often overlooked because their costs appear early in the project, while many of their benefits emerge later through reduced installation size, lower operational energy use and improved thermal resilience. Programme implications - Reserve budget for early climate simulations and passive studies - Include lifecycle performance alongside initial investment costs - Allow budget transfer between architectural and installation scopes	COST EXPERT CARD 11 HOW DOES UNCERTAINTY INFLUENCE INVESTMENT IN PASSIVE STRATEGIES? Fact Risk aversion and performance uncertainty often favour conventional mechanical systems. Programme implications - Use scenario-based costing approaches - Compare uncertainty between passive and active systems - Include robustness as economic value	COST EXPERT CARD 12 DOES TCO INFLUENCE BUDGET DECISIONS OR ONLY REPORTING? Fact Operational savings do not automatically translate into increased upfront passive investment. Programme implications - Link TCO outcomes to investment decisions - Evaluate long-term cooling reduction benefits - Include operational stakeholders in budgeting discussions	FACILITY MANAGEMENT CARD 25 CAN TEMPERATURE SETPOINTS VARY SEASONALLY OR BY USER GROUP INSTEAD OF REMAINING FIXED YEAR-ROUND? Fact Hospital comfort strategies are still largely based on fixed system criteria despite seasonal adaptation effects. Programme implications						

