AN ENERGY-EFFICIENT SYSTEM IN A SINGLE-LIVING RESIDENTIAL BUILDING IN THE NETHERLANDS

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ABSTRACT

Due to the need of sustainable housing and the rise of single-living population, the goal of this research is to explore an energy-efficient system which can achieve indoor comfort with minimum energy consumption in a single-living residential building in the Netherlands. With the analysis of the local climate and single-living pattern, energy-efficient technics are integrated into collaboration. Based on the integrated strategies and an architectural model, a prototype of the energy-efficient system is designed which operates correspondingly to different outside conditions. Further calculation examines the decisions of the system and helps to make more detailed design. Besides the energy-efficient system, this research also provides a basic method to simulate the design decisions and parameters in an energy-efficient system.

KEYWORDS

Single living, Housing, Energy efficiency, Heating, Cooling, Ventilation, Users' control

1 INTRODUCTION

In Europe, buildings account for 40% of total energy consumption and 36% of total CO2 emission.[1] Therefore, the reduction of architectural energy usage is essential and emergent for architects and engineers. Energy-efficient buildings are designed to reduce the amount of energy required and maintain a comfortable indoor environment. Passive strategies have priority, and active strategies help to supply comfort conditions when passive strategies aren't sufficient [2].

In the Netherlands, there are 1 million new homes needed by 2030, and the population of people living alone keeps rising (fig.1). This paper is the technical research related to the “Sustainable Single Living” design, and the research question is how to achieve indoor comfort with minimum energy consumption in a single-living residential building in the Netherlands.

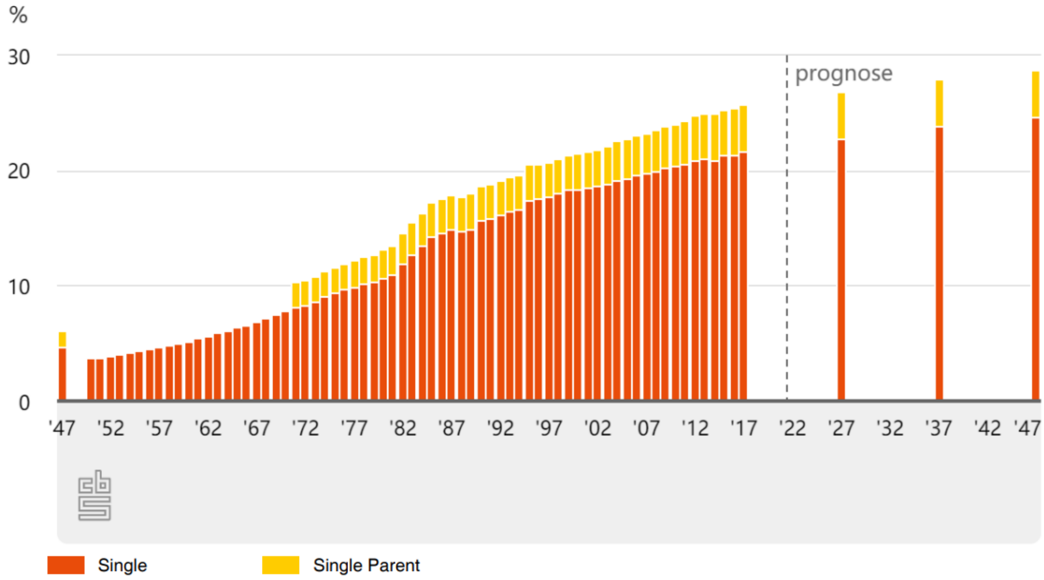


Fig.1 Single people and single parents in the adult population (%). Source: "One hundred years of single people" 25-6-2018 https://www.cbs.nl/nl-nl/achtergrond/2018/26/honderd-jaar-alleenstaanden

This technical research is a combination of architecture and engineering and paralleled with the design process. It also takes user behaviour and spatial design into consideration.

The research starts with the analysis of the climate and single living pattern. The strategies following are based on literature research and integrate single solutions into collaboration. The prototype of the energy-efficient system which is an integration of the strategies is described in different climate conditions in chapter 4. Finally, the calculation provides evidence and support of the prototype, and test more detailed parameters in the system.

The goal of this research is to give advice for the energy-efficient system in single-living housing design. In addition, it can provide a basic tool to analyse different design parameters and their effects on energy efficiency.

1. European Parliament and Council. 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union 2010. p. 13–35

2. Okay Go ̈nu ̇lol, Ayc ̧a Tokuc, Dinçer İbrahim. 2017. Net Zero Energy Residential Building Architecture in the Future. In C. Ozgur Colpan, and Onder Kizilkan, eds. 2018. *Exergetic, Energetic and Environmental Dimensions*. London, England: Academic Press. p. 39-53

2 THEORY

2.1 Climate

Climate parameters have great effects on the built environment and energy consumption. This research is related to the single-living design located in Rotterdam, so the climate data of Rotterdam is used for analysis and calculation.

Different from the conventional way of case studies and vernacular experience, the bioclimatic chart helps to find the need and potential energy strategies based on the local climatic data.[3]

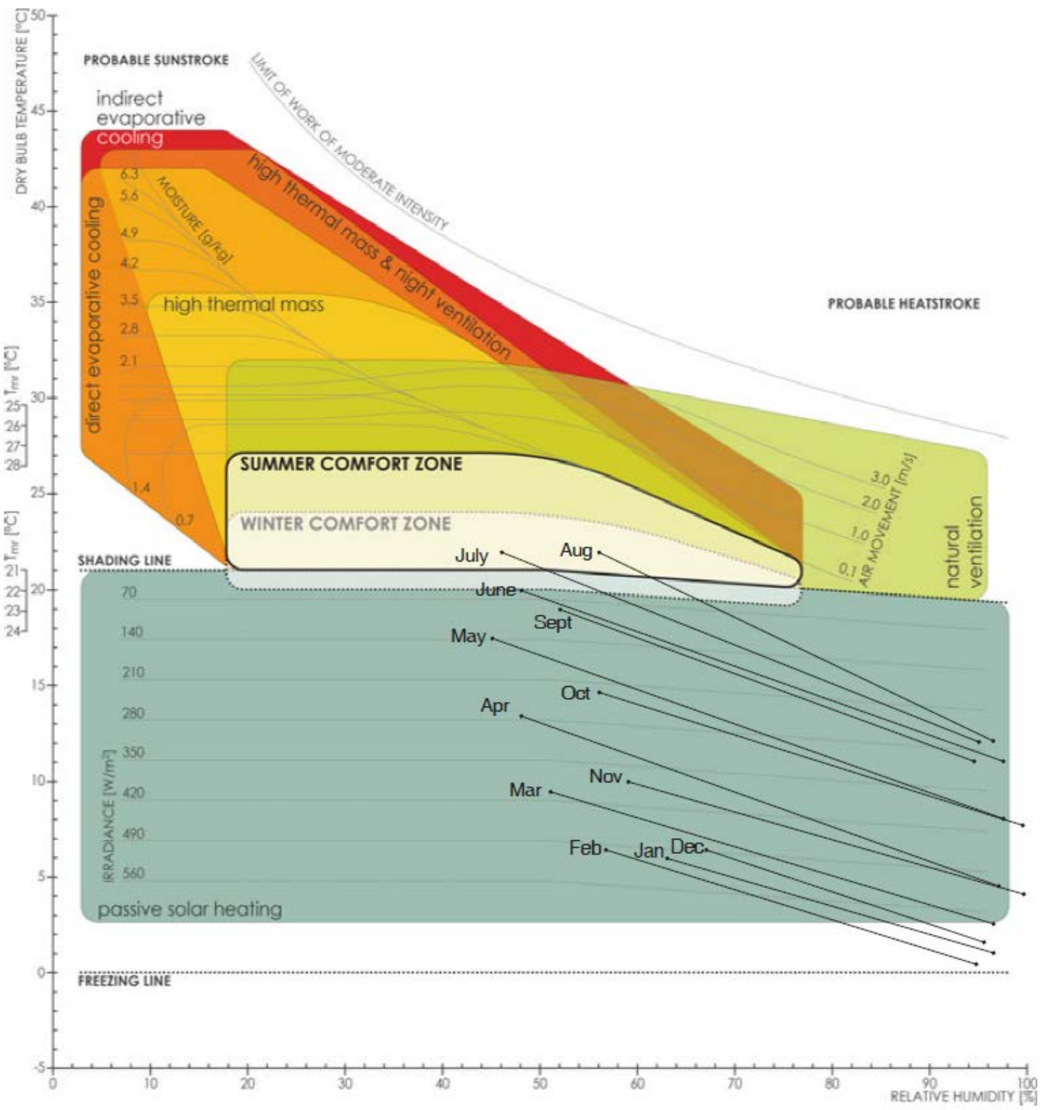


Fig.2 Bioclimatic Chart with the climate data of Rotterdam. Original: Košir Mitja. 2019. Climate Adaptability of Buildings: Bioclimatic Design in the Light of Climate Change. Cham, Switzerland: Springer. p.121

3. Brown, G. Z, and Mark DeKay. 2013. Sun, Wind, and Light: Architectural Design Strategies. Third [edition]. Hoboken: Wiley. p. E.339 - E.342

The conclusions of the chart include the following. Firstly, for most of the year, passive solar heating is helpful with the requirement of solar radiation from 70 W/m^2 to over 560 W/m^2. Secondly, because of the absence of solar energy during the night, heat storage is needed. Thirdly, when solar radiation is not enough for heating the building, for example in the coldest days from December to February, active heating generation is needed.

Besides the chart, other conclusions can be made based on the analysis of the local climate data[4]. Firstly, the solar radiation is extremely low during the winter because of the presence of clouds and the short sunshine hour (Table 1), so only passive solar heating is not reliable. Secondly, the short-term extreme hot temperature during the summer should also be taken into consideration, therefore solutions like night ventilation, proper shading, underground water cooling are needed to avoid overheating. Thirdly, the evaporation cooling is not suitable due to the high relative humidity. Fourthly, the solar heat is more efficient in the afternoon than in the morning due to the high outside temperature, so the west orientation is preferred in winter. Fifthly, the big seasonal differentiation of solar altitude (14 ° in winter and 61 ° in summer) can be used to get solar heat in winter while avoid overheating in summer.

Table 1 Solar radiation per hour (W/m2) Rotterdam. Source: http://www.soda-pro.com/home

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	4	1	0	0	0	0	0
5	0	0	0	2	25	44	28	4	0	0	0	0
6	0	0	1	34	97	133	100	49	12	0	0	0
7	0	0	30	128	216	247	211	140	85	16	0	0
8	1	21	113	256	339	362	332	248	199	84	15	0
9	31	83	212	362	436	472	434	319	308	174	68	21
10	84	151	273	419	503	552	511	356	388	222	118	65
11	129	209	307	462	527	592	537	375	435	251	150	95
12	156	229	319	496	536	575	537	416	431	252	166	108
13	146	216	304	479	534	580	562	405	398	238	151	97
14	112	196	279	439	488	533	517	381	354	205	106	69
15	62	139	225	383	436	485	467	331	293	145	55	29
16	15	70	166	298	362	414	400	291	205	72	9	2
17	0	14	80	175	258	313	294	190	98	12	0	0
18	0	0	13	66	139	185	179	98	20	0	0	0
19	0	0	0	8	45	76	71	21	0	0	0	0
20	0	0	0	0	3	14	10	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0

4. Remco Looman. 2017. “Climate-Responsive Design: A Framework for an Energy Concept Design-Decision Support Tool for Architects Using Principles of Climate-Responsive Design” 1 (1): 1–282. doi:10.7480/abe.2017.1. p. 73 - 96

2.2 Single living

In terms of energy consumption, compared to the conventional apartments, the three major characteristics of single living are bigger volume per person, specific usage pattern, and one big room.

Bigger volume

In the Netherlands, the living area per person for single-person households is 87.68 m^2, which is 26 m^2 more than average.[5] Bigger volume requires more energy to maintain indoor comfort. Therefore, the design of the small-size apartment (25-35 m^2 inside the unit) can help to reduce energy consumption.

Usage pattern

90% of the single-living population work outside their home.[6] Therefore it can be assumed that the main usage time is from evening till early morning on weekdays and the whole day on weekends. The regular schedule gives opportunities for heating or cooling only when needed. (Fig 3) The smaller space size and floor heating/cooling also make it possible to achieve indoor comfort in a short time.

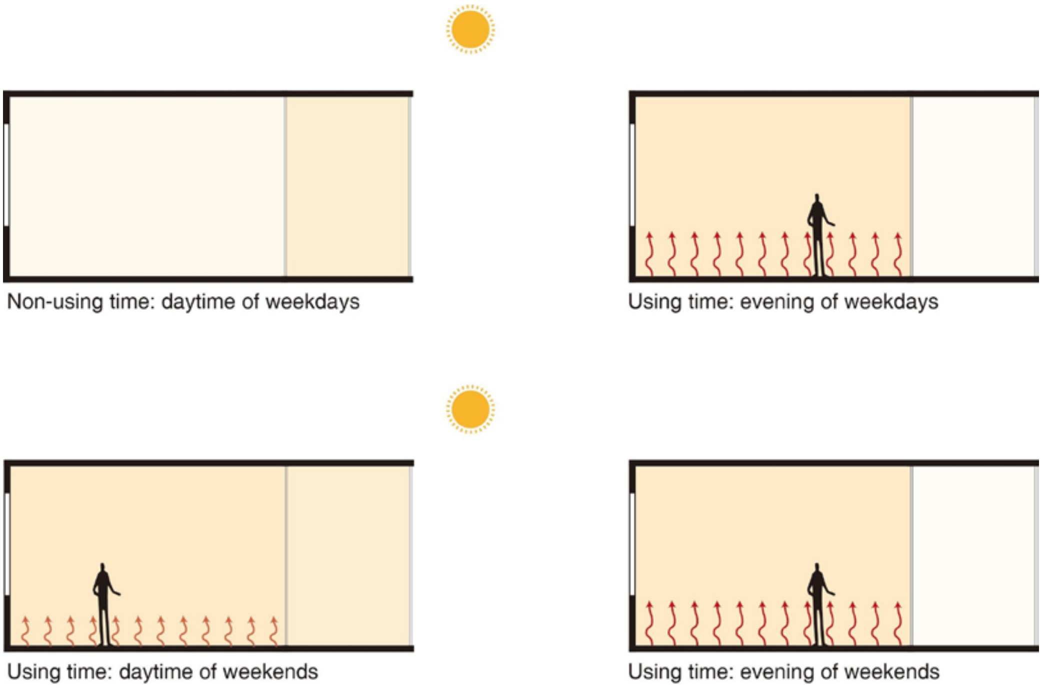


Fig 3 Heating control according to the usage pattern

Single living sometimes means poor control of the living environment, for example, if the habitant forgets to turn off the heating during the winter day or put down the shading during the summer day, no one else could help. However, an automatic control system that changes once in a few minutes can be annoying for users. Therefore the possible solution could be the combination of users' control and automatic control. The automatic control acts once every three hours while the priority still belongs to users.

5. https://www.cbs.nl/nl-nl/nieuws/2018/22/amsterdamse-huishoudens-hebben-minder-woonoppervlakte

6. CBS data from https://opendata.cbs.nl/statline/#/CBS/en/dataset/82956ENG/table?ts=1579178150364

One big room

According to the WHO report, the advised indoor temperature are living areas 21 °C, kitchen and circulation areas 16 °C, bathrooms 21 °C, bedrooms 18 °C. [7] However, the single-living studio usually has only one big room which includes the function of bedroom, living room, dining room and kitchen. The conventional apartment can set lower temperature for bedroom and kitchen to reduce the heating load, which is not the case for the single-living apartment. (Fig 4)

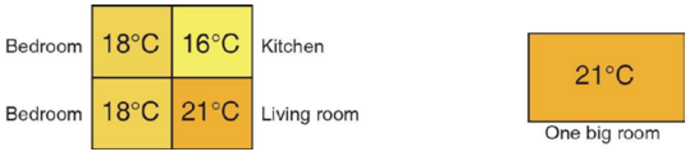
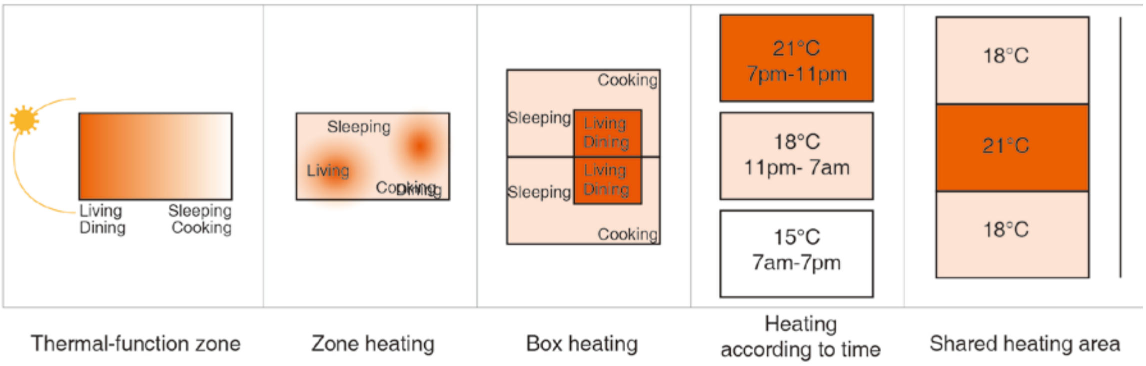


Fig 4 Difference of design temperature between a conventional apartment and single-living studio

There are several possibilities for this issue (Table 2).

Table 2 Five solutions to reduce heat demand in one big room



Thermal-function zone: Put the high-temperature-requiring functions to the southern side and make use of solar heat. It limits the flexibility of the layout and may cause the problem of privacy since the sleeping area is near the northern entrance. In winter, the solar heat is not stable.

Zone heating: Higher temperature is only provided by decentralized heating in small areas according to different functions zones. The temperature difference is not significant in an open space and it needs an extra heating system. But it keeps the flexibility of the layout.

Box heating: Higher temperature functions are centralized in one area separated from the rest space by movable walls. It improves the efficiency of temperature difference, but the flexibility is limited and an extra heating system and walls are needed. In addition, the walls of the heated area of different apartments can be put together to reduce the energy consumption.

Heating according to time: Because there is only one habitant, so different time means different functions. The temperature in the big room changes according to daily activities. While sleeping time, the temperature is 18 °C, working/living time, 21 °C. It needs an accurate control system and the schedule of different users needs to be customized.

Shared heating area: During the cold period, inhabitants share a warm common living and dining room, the temperature inside each studio can be lower only for sleeping. It also enhances the social connection but limits the usage flexibility of individual units. Extra sharing spaces are needed.

7. WHO. 1988. Guidelines for Healthy Housing. p. 149
https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012_nvt/artikelsgewijs/hfd9/art9-2

3 STRATEGIES

Based on the analysis above and the literature study, this part includes some energy-efficient strategies which are considered suitable for applying in the design of the single-living residential buildings in the Netherlands.

3.1 Orientation and solar gain

As Brown[8] indicates, if the solar collection glazing is within 30° east or west of equatorial, the decrease in solar gain performance will be less than 10% of the optimum. And variations in orientation up to 40° from perpendicular to the prevailing wind do not significantly reduce ventilation. Therefore, the best orientation is around 210° (SW-SSW) considering the dominant wind direction 247°.

Under certain urban context, it is hard to achieve the best orientation for both solar gain and cross ventilation. An alternative way is combining the orientation for solar gain (between 150° to 210°) and stack ventilation. However, the solar heat is more efficient in the afternoon than in the morning due to the high outside temperature, so the west orientation is preferred for winter when it is possible.

To get as much solar heat as possible in winter, the southern façade can be totally glazed. But it needs a proper shading system during summer daytime to avoid overheating. The glazing façade might cause heat loss during the night which can be improved by movable insulation controlled by users or automatically, for example, curtains or panels. Lined curtains can reduce the heat loss by around 10% [9], and XPS panels (20mm) can reduce the heat loss by around 50% [10].

3.2 Migration and buffer zones

Migration means residents are flexible to move to the area that they find most comfortable during day or night, summer or winter.[11] One example of this strategy is Pueblo Acoma, near Albuquerque, New Mexico. (Fig 5) In cool seasons, the outside terraces are used during the day and the interior spaces at night. In the warm season, the reverse is true: The outside terraces are used at night and the shaded cool interiors during the day. [12]

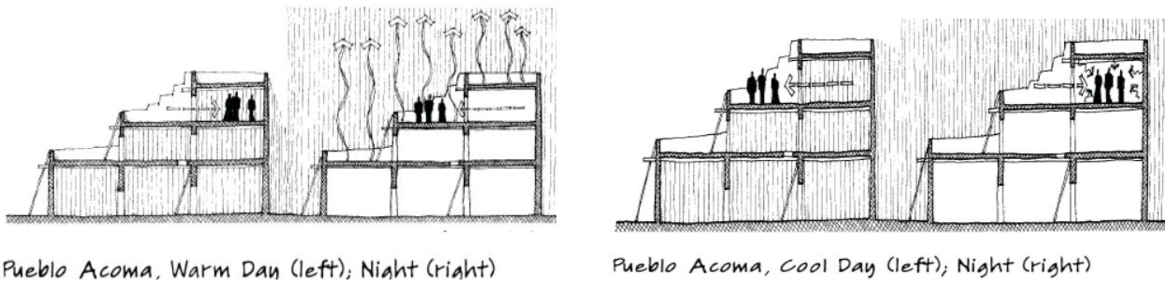


Fig 5 Migration of residents to find comfort area. Brown, G. Z, and Mark DeKay, 2013. p. 224.

8.11. Brown, G. Z, and Mark DeKay. 2013. Sun, Wind, and Light: Architectural Design Strategies. Third [edition]. Hoboken: Wiley. p. 224-235

9. Fitton, R., Swan, W., Hughes, T. et al. Energy Efficiency (2017) 10: 1419. https://doi.org/10.1007/s12053-017-9529-0

10. Alsaad, Hayder & Chang, Jae. (2014). The Efficiency of Night Insulation Using Aerogel Filled Polycarbonate Panels During the Heating Season. Journal of The Korean Society of Living Environmental System. 21. 570-578. 10.21086/ksles.2014.08.21.4.570.

12. Nabokov, Peter. 1986. Architecture of Acoma Pueblo: The 1934 Historic American Buildings Survey Project, Historic American Buildings Survey. Santa Fe, NM: Ancient City Press

This strategy can be combined with the annual control of the indoor environment. Researches show that if inhabitants have some form of input to the control of their own indoor environment, their subjective view of comfort zone changes and they are more willing to accept wider conditions.[13] For example, opening a window for fresh air and natural ventilation, choosing different areas for daily activities during winter and summer, pulling down the shading, and turning on the heating system.

Because migration needs more choices of the space with different thermal conditions, the buffer zone strategy can be integrated with it. For instance, a balcony on the south side can be a buffer zone during the winter night, but it becomes a desirable space during winter daytime with warm sunlight. The balcony can also provide shading during summer daytime acting as a buffer zone and becomes comfort outdoor terrace during summer night with the openable window. (Fig 6)

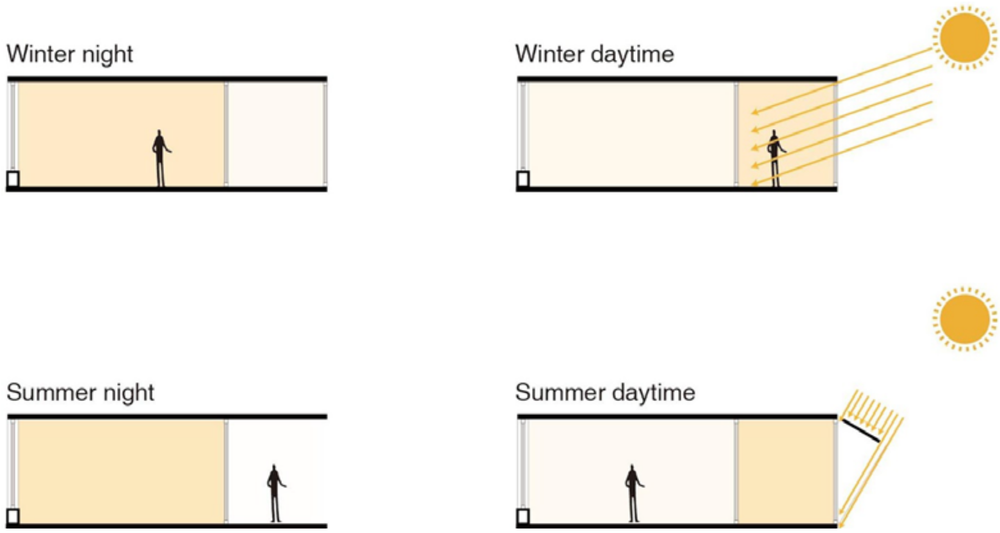


Fig 6 Balcony acts as a buffer zone and migration space in different conditions

3.3 Solar chimney and stack ventilation

Ventilation can cause lots of heat loss and mechanical ventilation lacks choice and control for users. Therefore, the goal is to achieve natural ventilation as much as possible at the same time reduce heat loss and energy consumption.

Solar chimney and atrium provide a tall space for the heated air to rise, and stack ventilation makes use of this physical principle and organizes the air movement without extra energy. In addition, during the summer, the heated air from the solar chimney can be transfer into domestic hot water by a heat pump on the top.

The ventilation is designed in two basic conditions: maximum free-running and limited mode. When the outside temperature is mild or during the summer night, the maximum fresh air goes in through the open outside façade and inner façade towards the atrium and rises up. Finally, it goes out through the openable roof and takes the extra heat out of the building. When the outside temperature is too cold or too hot, the outside façade is closed, ventilation conducted with the inner atrium and helped by the solar chimney (with openable holes towards all individual balconies). The atrium controls the air change rate to its minimum and acts as a buffer zone. A heat recovery system can provide pre-heated fresh air into the atrium to reduce heat loss. (Fig 7)

13. Lim B P, Hijazi H, Thiébaux S, et al. 2016. Online HVAC-Aware Occupancy Scheduling with Adaptive Temperature Control[C]. //International Conference on Principles and Practice of Constraint Programming. Springer, Cham. p. 683-700.

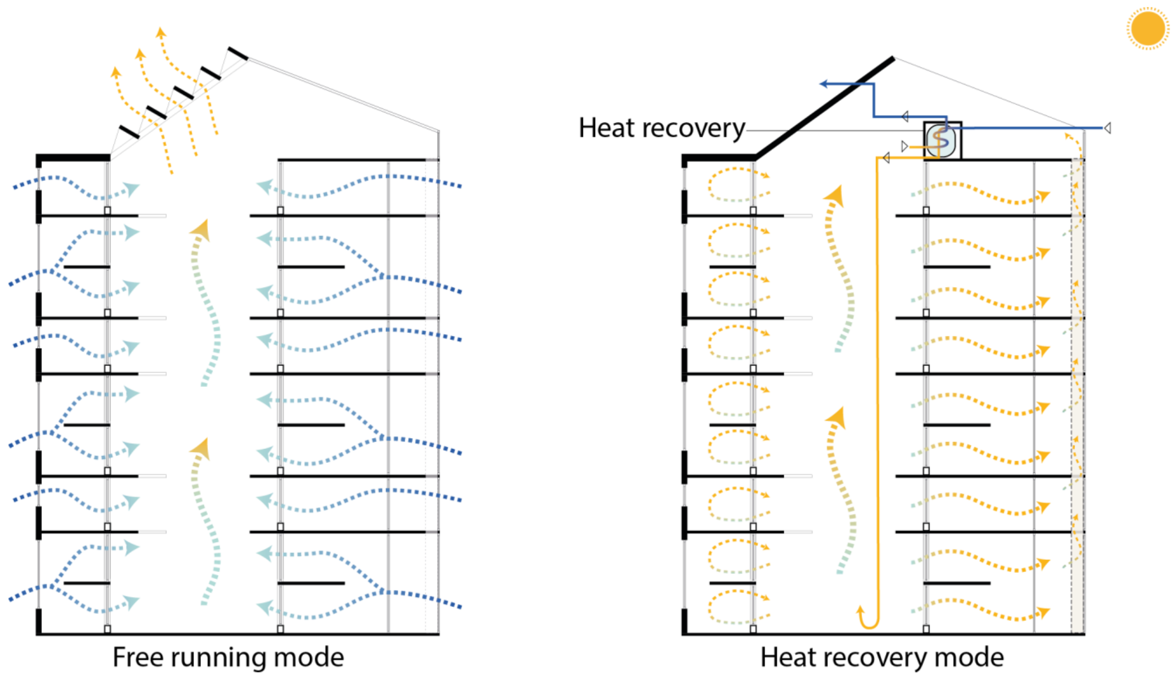


Fig 7 Two modes of stack ventilation

3.4 Geothermal-source heat pump and LTH (low-temperature heating)

The heat pump can achieve high exergy comparing with an electrical heater. (Fig 8) And the free environmental heat or cool source from geothermal water storage leads to the lower energy consumption of heating and cooling. The geothermal-source considered in this research is around 60 meters, which has a relatively stable temperature of 12 °C.

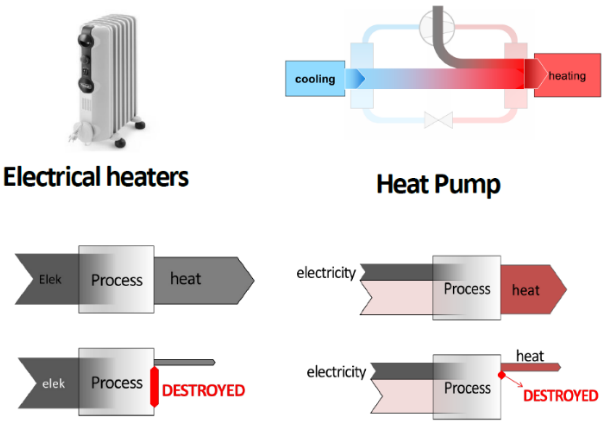


Fig 8 Comparison between electrical heating and heat pump in terms of energy and exergy. Sabine Jansen, 2019, Lecture Exergy and sustainable urban energy systems

According to Sabine Jansen, the COP (coefficient of performance) of the heat pump is determined by the temperature difference between the source temperature and target temperature. The less the difference, the more efficient it is.[14] Therefore, low-temperature floor heating (around 40°C) combined with a geothermal-source heat pump can achieve high energy efficiency. (Fig 9)

14. Sabine Jansen. 2014. Exergy Guidebook for Building Professionals. Version 2. Delft University of Technology. https://klimapedia.nl/publicaties/exergy-for-building-professionals/ p. 47-48

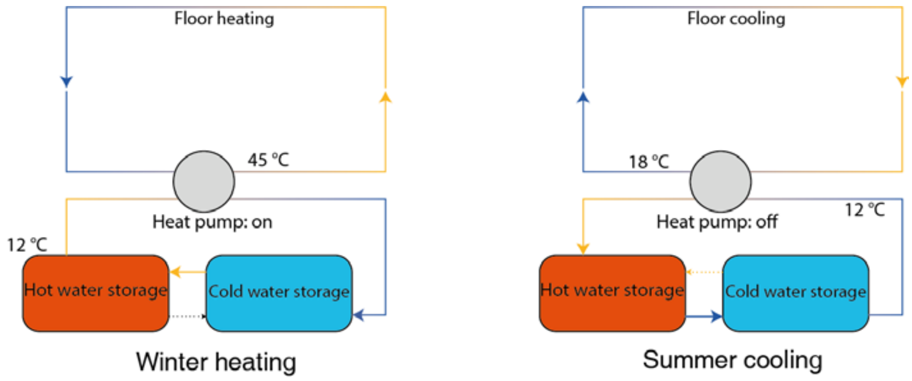


Fig 9 floor heating/cooling system combined with geothermal-source heat pump

3.5 PCMs (Phase Change Materials)

Thermal mass in a building consists of two parts: the construction and PCMs. PCMs can store or release a large quantity of thermal energy by changing its state between liquid and solid in a smaller volume.[15]

In winter, it can store solar heat during the day and warm up the indoor space at night. In summer, it stores cooling via the night ventilation and cools down the space preventing overheating during the daytime. With floor heating and cooling system, the location of PCMs can be in the ceiling inside and on the floor in the balconies. (Fig 10)

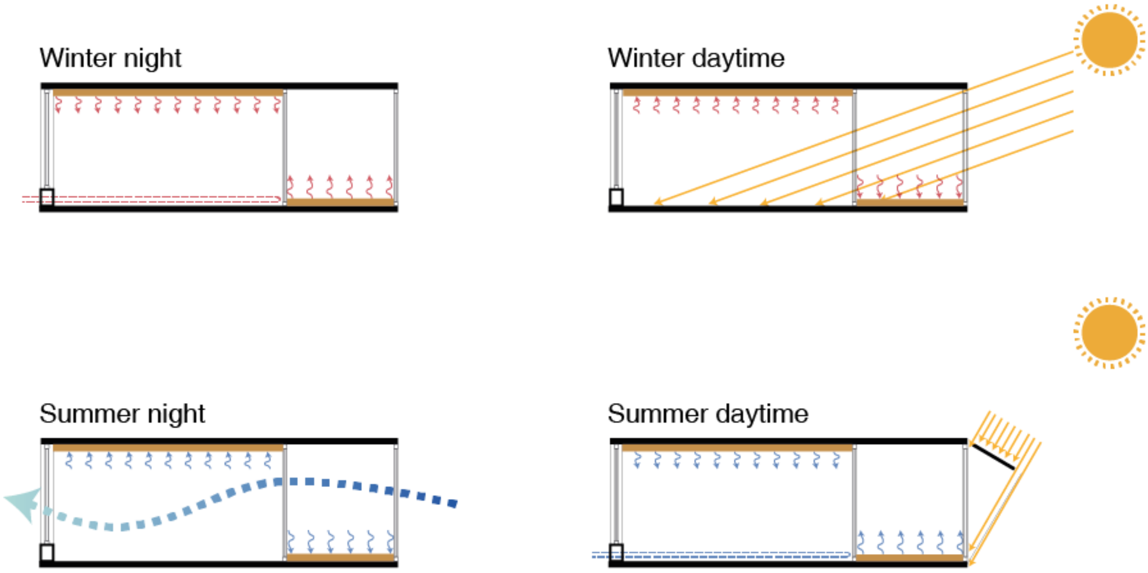


Fig 10 PCMs in winter and summer combined with floor heating or cooling

15. Brown, G. Z, and Mark DeKay. 2013. Sun, Wind, and Light: Architectural Design Strategies. Third [edition]. Hoboken: Wiley. p. E203

3.6 Green

Except for the psychological function, food production and purification of the air, green elements in the atrium can also act as absorption of excess solar heat and provide shading in summer. The solar angle is high in summer, most of the direct sunlight is absorbed by the plants on the roof floor. While with a lower solar angle in summer, most of the direct sunlight goes into the atrium and heat the air inside. (Fig 11) Meanwhile, it helps to improve the acoustic environment in the atrium.

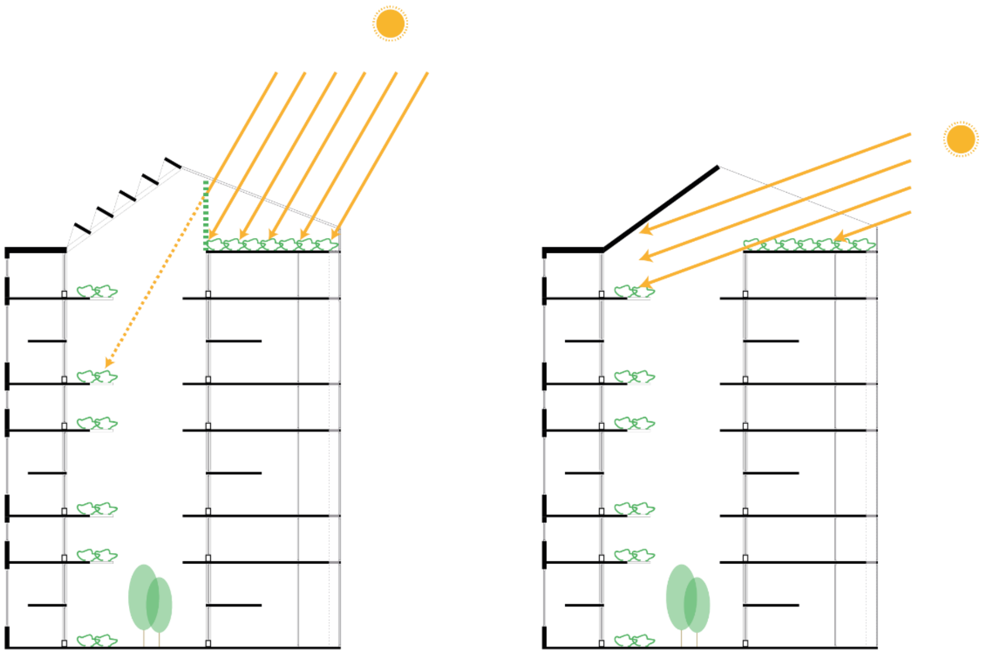


Fig 11 Green elements in the atrium

4 PROTOTYPE

4.1 Architectural model

The research is paralleled with the architectural design. Therefore the elements to achieve energy efficiency like the atrium, the solar chimney and the balcony are considered within the design from the beginning. (Fig 12) The area inside each single-living studio is small (between 25 m^2 to 35 m^2) including a minimum function area and extended personality space. The sharing common space enhances the social cohesion and provides the possibility of centralized heating mentioned above. The architectural model also gives the dimensions for further calculation.

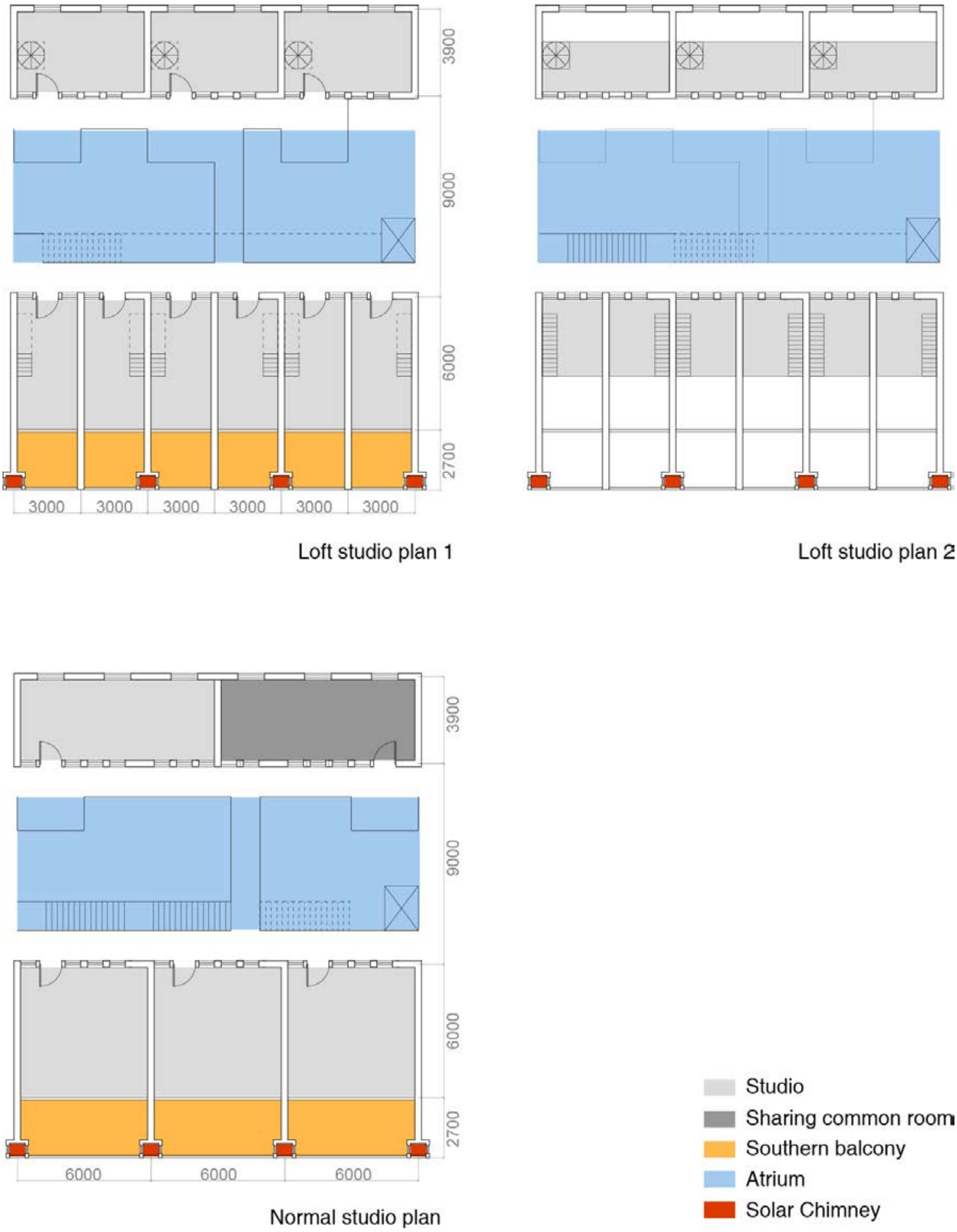


Fig 12 Plans of a studio cluster

4.2 Energy-efficient system

The operation of the system is corresponding to the outside condition over the year. Five conditions are defined based on the temperature of daytime and night. Under each condition, individual elements are collaborating to achieve indoor comfort with minimum energy consumption (Table 3).

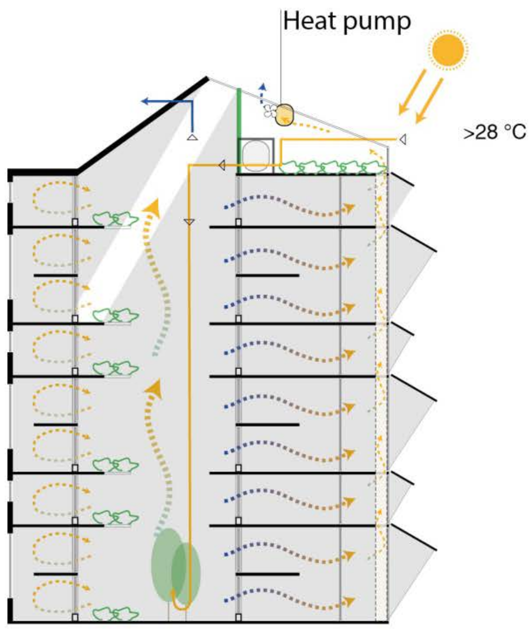
Table 3 Adaptive system elements for five conditions in a year (√= on, O = off)

	Hot summer		Warm summer		Mild season		Cool winter		Cold winter	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Outside temp.	>28 °C	>15 °C	20 °C	>15 °C	>15 °C	12 °C	12 °C	≤ 10 °C	≤ 10 °C	≤5 °C
Diagram No.	1-a, 1-b	1-c	2-a, 2-b	2-c	3-a	3-b, 3-c	4-a	4-b, 4-c	5-a, 5-b	5-c, 5-d
Outside facade	O	√	√	√	√	O	O	O	O	O
Chimney window	√	O	O	O	O	√	√	√	√	√
Openable roof	O	√	√	√	O	O	O	O	O	O
Heat recovery	O	O	O	O	O	√	√	√	√	√
Attic heat pump	√	O	√	O	√	O	O	O	O	O
PCMs	Cool out	Cool in	Cool out	Cool in	Warm in	Warm out	Warm in	Warm out	Warm in	Warm out
Floor heating	O	O	O	O	O	O	O	O	O	√
Floor cooling	√	O	O	O	O	O	O	O	O	O
Movable insulation	O	O	O	O	O	O	O	√	O	√
Attic division	√	O	√	O	O	O	O	√	O	√
Southern shading	√	O	√	O	O	O	O	O	O	O

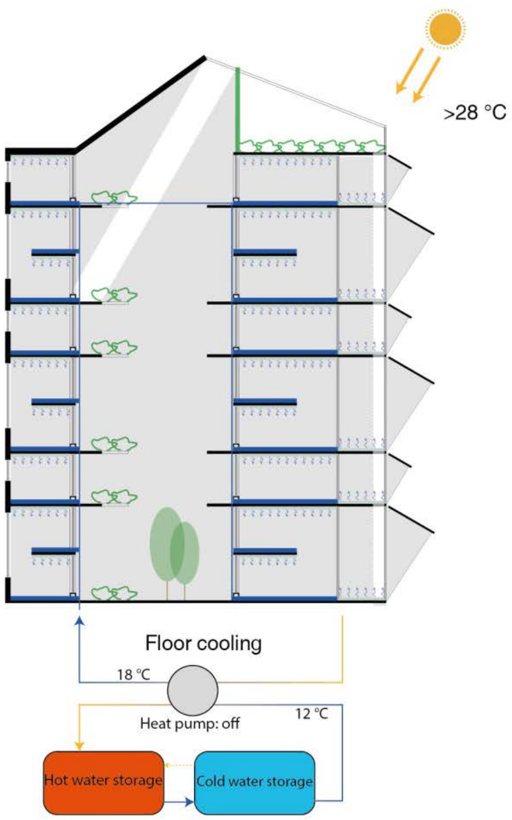
The system can be controlled automatically by a computer program based on the outside climatic conditions. The automatic control acts once every three hours while the priority of some elements like outside façade, chimney window and southern shading still belongs to users.

Hot summer:

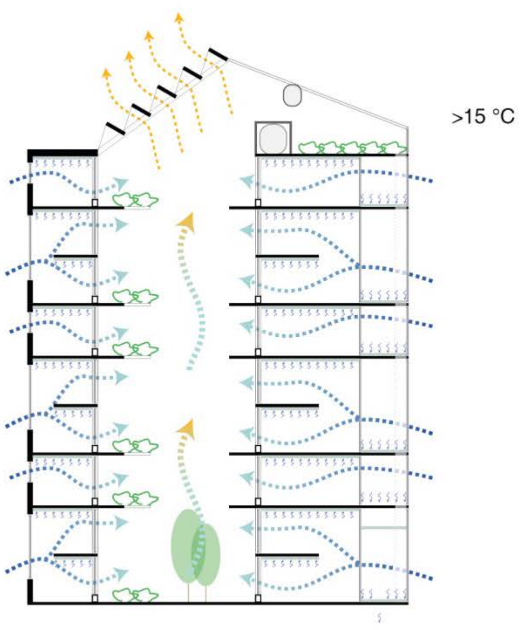
[1-a] Hot summer day ventilation



[1-b] Hot summer day cooling



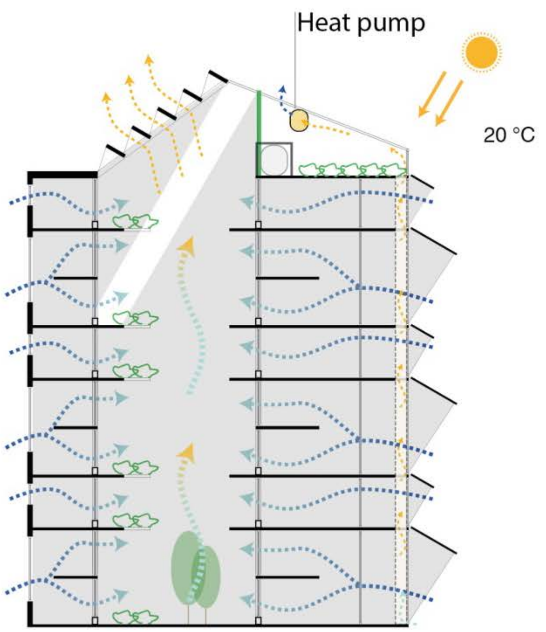
[1-c + 2-c] Free-running night ventilation



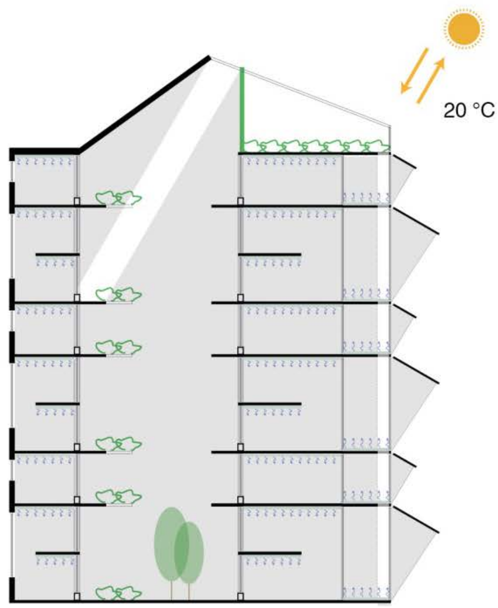
In the daytime, the ventilation is limited to the minimum with the atrium and solar chimney system. The shading system prevents excessive solar heat entering the building and the extra solar heat is transferred to domestic hot water. PCMs and the underground water storage provide cooling to the building and the atrium and balconies act as the buffer zone. During the night, the maximum night ventilation is applied to cool down the building and PCMs in the ceiling inside and on the floor in the balconies..

Warm summer:

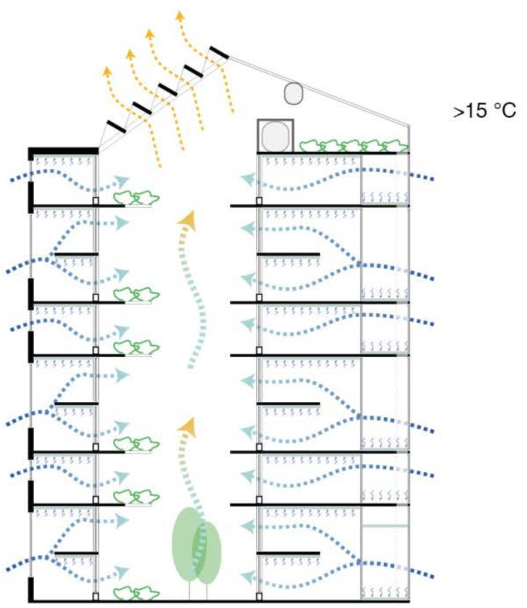
[2-a] Warm summer day ventilation



[2-b] Warm summer day PCM cooling



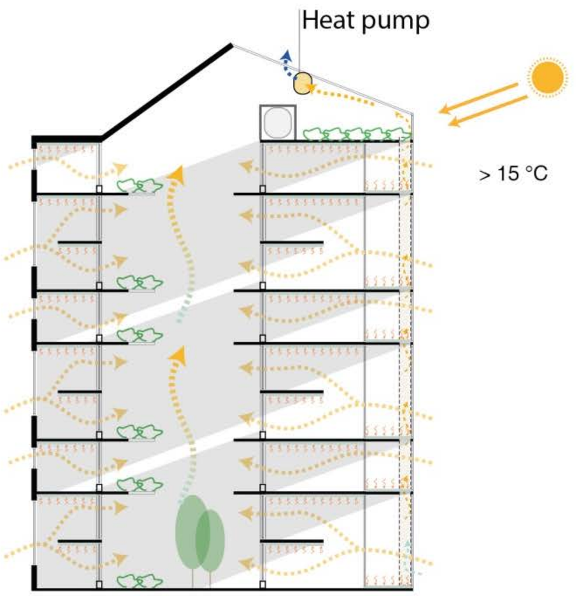
[1-c + 2-c] Free-running night ventilation



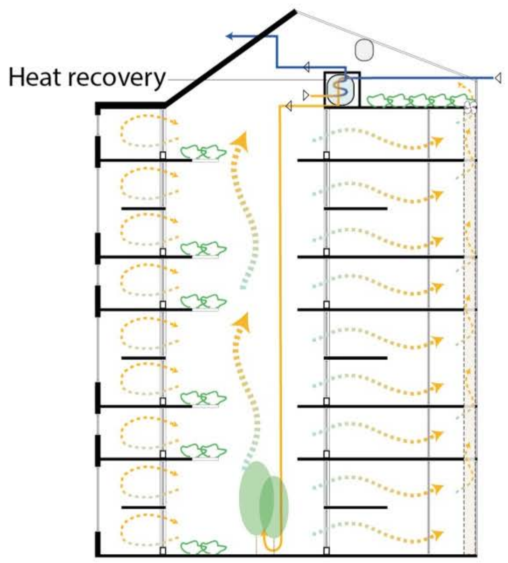
In the daytime, maximum ventilation is used to remove heat from the building. The shading system prevents excessive solar heat entering the building and the extra solar heat is transferred to domestic hot water. PCMs provide cooling to the building. During the night, the maximum night ventilation is applied to cool down the building and PCMs.

Mild season:

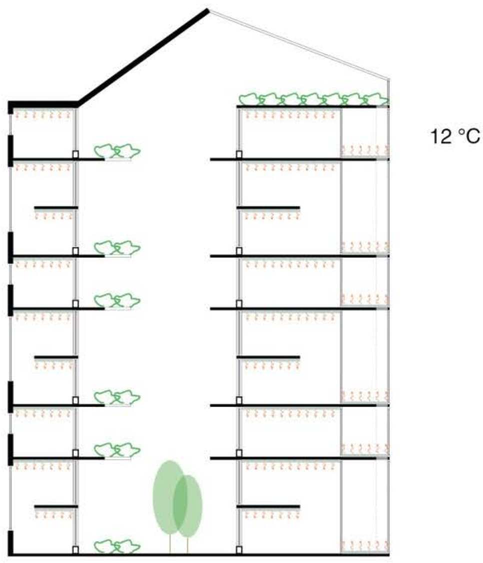
[3-a] Mild day ventilation



[3-b + 4-b + 5-c] Night HR ventilation



[3-c] Night PCM heating



In the daytime, natural stack ventilation is organized with the atrium and heat pump and the extra solar heat is transferred to domestic hot water. Sunlight heats the building and melts the PCMs. During the night, minimum heat recovery ventilation conducted by the atrium and the solar chimney reduces the heat loss. PCMs provide heating to the building. The atrium and balconies act as the buffer zone.

Cool winter:

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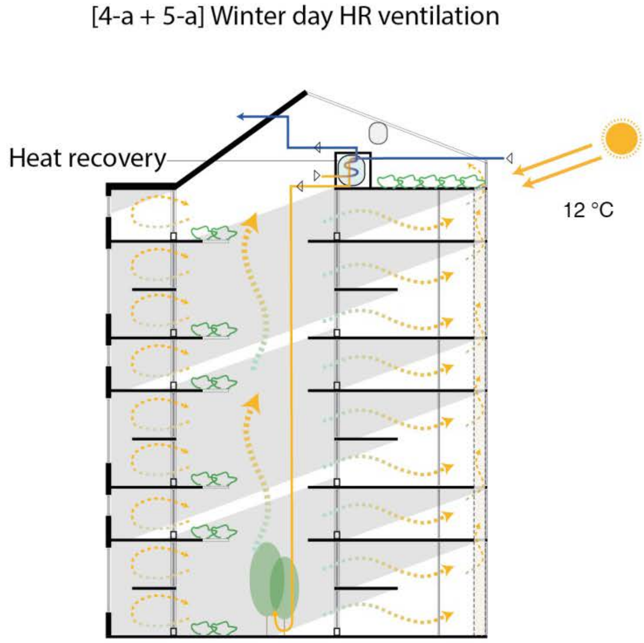
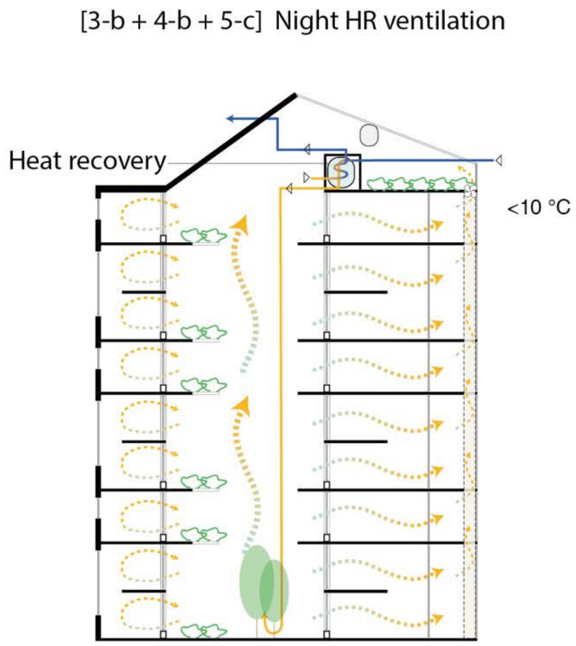
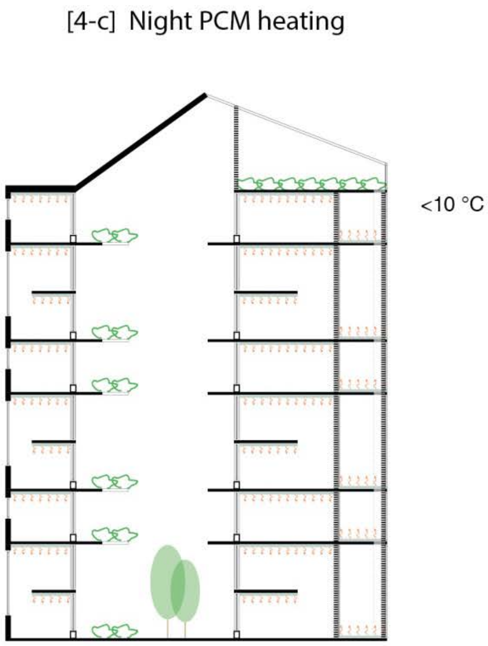


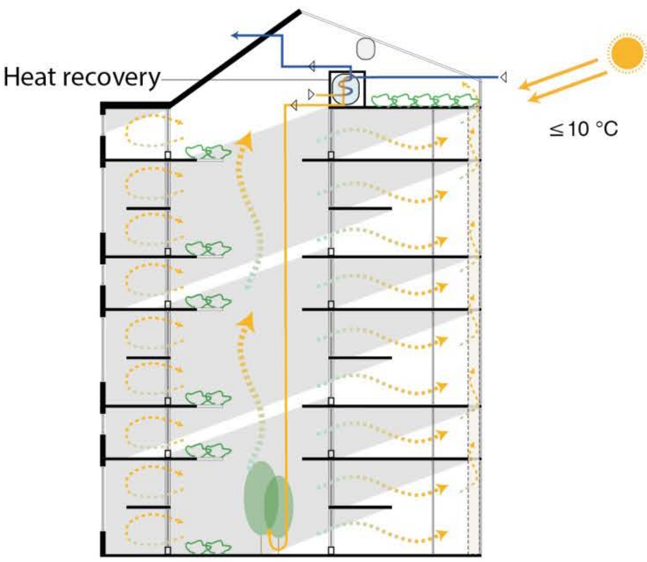




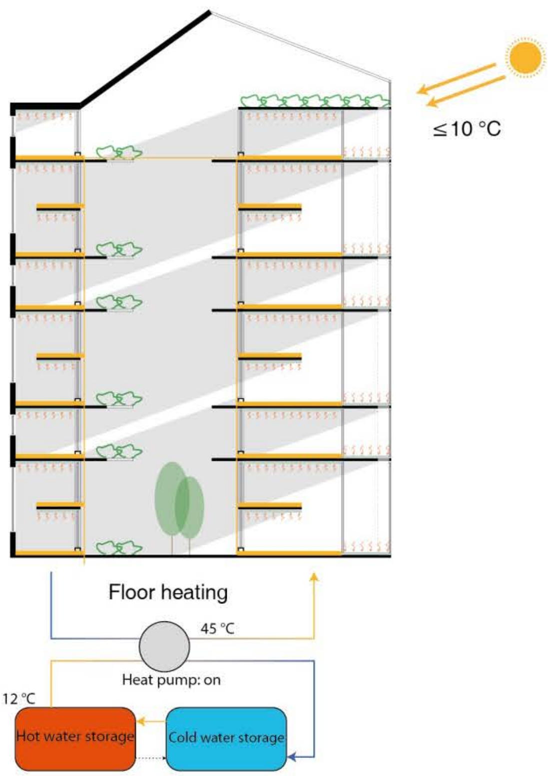
In the daytime, the heat recovery ventilation is limited to the minimum with the atrium and solar chimney system. Sunlight heats the building and melts the PCMs. During the night, minimum heat recovery ventilation conducted by the atrium reduce the heat loss. PCMs provide heating to the building. The atrium and balconies act as the buffer zone and the movable insulation is applied to reduce the heat loss through the envelope.

Cold winter:

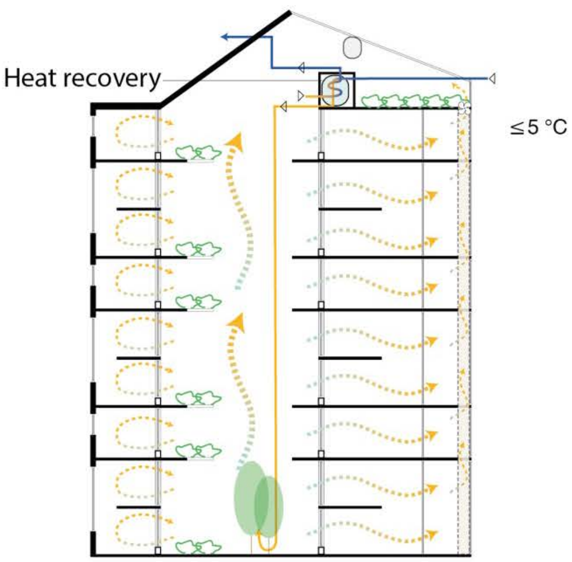
[4-a + 5-a] Winter day HR ventilation



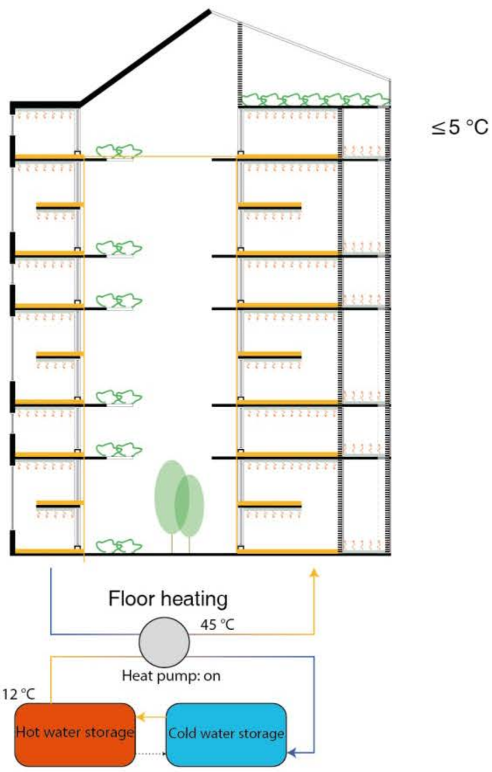
[5-b] Cold winter day heating



[3-b + 4-b + 5-c] Night HR ventilation



[5-d] Cold winter night heating



Winter heating

Besides the cool winter condition, heat pump with underground water storage provides low-temperature floor heating when needed.

5 CALCULATION AND RESULTS

The purposes of the calculation are to exam some decisions in the system, analyse detailed design parameters and their effects on energy efficiency, for instance, the wall-window ratio, and try to balance between the summer and winter, day and night.

5.1 Parameters

Fixed parameters

To simplify the complicated factors, some inputs are assumed to be fixed (Table 4). These fixed parameters are related to the above architectural model, the energy-efficient system and the certain context.

Table 4 Fixed input parameters of the calculation

Fixed input parameters	Value	Remark
Orientation	32.2° (SE)	
Area inside apartments	1245.3 (m^2)	
Total volume	9914.4 (m^3)	
Population of residents	36 (persons)	
Facade area	459 (m^2)	
Roof tilted angle	21°	
Southern tilted roof	198 (m^2)	Glazing but can have the collection of solar hot water
Southern vertical roof	27 (m^2)	
Northern tilted roof	198 (m^2)	Not glazing and can open for ventilation
Horizontal roof	72 (m^2)	

The outside temperature and solar radiation value are based on the local climate data.[16] While in the calculation, the extreme condition will also be considered (winter night outside temperature -10 ℃, summer day outside temperature 35 ℃, solar radiation of summer daytime 800W/m^2). Based on the WHO report, the design temperature is assumed as 25 ℃ for summer and 2[17] This simplifies the calculation but ignores the differentiation of design temperature for different function area mention in chapter 3.

Test parameters

Besides the energy-efficient model, there are more detailed design decisions and parameters that affect the heat flow and energy efficiency which include U-value of the glazing and closed part (U_g, U_{closed}), window-to-wall ratio (WWR_{south}, WWR_{north}), and the g-value of the glass (g). In the calculation part, these test parameters can be adjusted to achieve a better result based on the system. For the primary calculation, the default values are used (U_g = 1.1 W/m^2K, U_{close} = 0.2 W/m^2K, WWR_{south}= 1, WWR_{north}= 0.4, g=0.6).

In addition, the effects of strategies like manually opened windows for night ventilation (default F_{vent}=1), and half-automatically half-manually shading system (default $F_{shading}$=1) depends largely on users' cooperation. So, by testing these parameters, the results give the idea of how the unsure using pattern can affect the whole system.

16. Outside temperature and solar radiation 2013-2016 from PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html

17. WHO. 1988. Guidelines for Healthy Housing. https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012_nvt/artikelsgewijs/hfd9/art9-2

5.2 Calculation methods

The calculation is carried out for the hottest hour in the summer day and coldest hour in the coldest winter night in order to provide guarantees for the indoor comfort. In addition, daily calculation helps to better understand the whole circularity of heat through the building during a day.

The heating/cooling demand is determined by internal heat load, heat conduction through the envelope, solar heat gain, and ventilation heat transfer. These four factors tell the heating/cooling demand for the hour. The calculation of the whole day is the accumulation of 24 hours with the changing outside temperature and solar radiation (the calculation can be seen in the appendix). And the calculation of PCMs and heat pump are to meet the demand and maintain the indoor comfort.

$$Q_{demand} = Q_{Inte} + Q_{Envelope} + Q_{Solar} + Q_{Vent} = Q_{PCMs} + Q_{Heat\ pump}$$

Internal heat load

According to Brown[18], the internal heat generation consists of two parts: people and equipment $Q_{People\ and\ equipment} = 9W/m^2$, and the average lighting factor $Q_{Lighting} = 3\ W/m^2$. The value is estimated based on the type of design and the latitude. The result is 14943.6 W hourly (415 W per apartment) and 358646.4 Wh for the day.

$$Q_{inte} = A_{floor\ area} \times \left(Q_{People\ and\ equipment} + Q_{Lighting}\right) = A_{floor\ area} \times 12\ (W/m^2)$$

Exclusive:
More internal heat generation due to the floor area outside the apartment is not included.

Heat conduction through the envelope

The heat conduction through the envelope is the total of glazing and closed area.

$$Q_{envelop} = [A_{glass} \times U_g + A_{closed} \times U_{closed}] \times (T_{outside} - T_{inside})$$

After putting into all fixed parameters and remains the test ones, the final formula is:

$$Q_{envelop} = \{(459 \times (WWR_{south} + WWR_{north}) + 225) \times U_g + [459 \times (2 - WWR_{south} - WWR_{north}) + 270] \times U_{closed}\} \times (T_{outside} - T_{inside})$$

The hourly results with the default test parameters are -23395.68 W (extreme -31903.2 W) for winter and 3190.32 W (extreme 10634.4 W) for summer. The daily results are -543524.184 Wh for a winter day and -14143.752 Wh for summer.

Exclusive:
Less heat loss can be achieved due to the double façade of the southern balcony. But under the coldest and hottest situation, the ventilation is through the inner façade to the solar chimney, so the actual U-value is less than a real double façade.

Less heat loss can be achieved due to the application of movable insulation during the winter night.

18. Brown, G. Z, and Mark DeKay. 2013. Sun, Wind, and Light: Architectural Design Strategies. Third [edition]. Hoboken: Wiley. p. E350-353

Solar heat gain

The solar radiation data used here is based on the location and the architectural model mentioned above. The tilted glazing roof is calculated differently from the vertical southern façade.

$$Q_{Solar} = A_{glass\_tilted} \times g \times Q_{sun\_tiled} + A_{glass\_vertical} \times g \times Q_{sun\_vertical}$$

The hourly results with the default test parameters are 0 W for winter, and 405669.6 W for summer. The daily results are 291409.92 Wh for a winter day and 2046997.5 Wh for summer.

With the movable shading system, the solar heat gain is less in the summer. The shading efficiency ($E_{shading}$) is simulated by dividing the whole façade area by shading area per hour (detailed results in the appendix). The tilted angle is 30° and the depth the shading panel is assumed as 1200mm. The results are 100% for the hottest hour and 80% for the average of the day. However, the movable shading is partly controlled by the users and partly by the automatic system, so the result is multiplied by a shading factor (default $F_{shading}$=1) related to the users' using pattern.

$$Q_{Solar} = A_{glass\_tilted} \times g \times Q_{sun\_tiled} \times (1 - E_{atrium\_shading}) + A_{glass\_vertical} \times g \times Q_{sun\_vertical} \times \left(1 - E_{shading} \times F_{shading}\right)$$

Exclusive:
There is more solar heat gain in summer due to the heat transfer with the warm space on the top of the atrium where the heat pump transfer the solar heat to domestic hot water.

Ventilation heat transfer

$$\mathrm{Q}_{vent} = \left(q_V \times (1 - hrp) + q_{inf}\right) \times \rho \times \mathrm{c} \times (T_{outside} - T_{inside})$$

During the hottest and coldest situation, a minimum air change rate of ventilation (1.3 volume/hr) is required. So the total q_v is 3.58 m^3/s. Besides, the air infiltration is assumed as 0.2 volume/hr, so the total q_{inf} is 0.55 m^3/s.

The heat recovery system is used (hrp = 70%) in the winter and off (hrp = 0) during the summer in the system. The density of air (ρ) is 1.2 kg/m3, the specific heat of air (c) is 1000 Ws/(kgK).

The hourly results are -42873.6 W (extreme: -58464 W) for winter, and 14868 W (extreme: 49560 W) for summer.

When it comes to the daily calculation, according to the system, summer night ventilation is applied for cooling down the building during the night. The air change rate of night ventilation is assumed as 5 volume/hr (q_{night} = 13.77 m^3/s), and the duration of it is from 7 pm to 5 am. Similar to the shading system, the effect of night ventilation also has a user factor (default F_{vent}=1). If users are not willing to open their windows at night, the cooling effects will reduce.

$$\mathrm{Q}_{night} = q_{night} \times \rho \times \mathrm{c} \times \sum_{7\,pm}^{10} (T_{outside} - T_{inside}) \times F_{vent}$$

The daily results are -996031.68 Wh in the winter and -670355 Wh (including night ventilation -644436 Wh) in the summer.

PCMs

In the hottest or coldest hour, PCMs act as a free source of cooling or heating. The amount of heat it can absorb or release is determined by the material, the amount and the construction way. The theoretical calculation is based on its specific heat of fusion (H_{fus}, kJ/kg), which can be estimated at around 200 kJ/kg[19] considering the suitable melt temperature for the living environment.

$$\mathrm{Q}_{PCMs} = m_{PCMs} \times H_{fus}/3.6$$

Based on this formula, if the demanding heat of PCMs is known, the amount of PCMs (m_{PCMs}, kg) can be calculated.

In addition, a practical calculation can also be used to verify the result. C3 - Phase Change Material klimaatplafonds from ORANGE CLIMATE installed in the ceiling has the capacity of 30 W/m^2 under the temperature of 18℃ and the ventilation of 4.5 m^3/hm^2.[20] Thus, the total heat can be achieved is 37359 W which equals 672.5 kg in the building (17.2 kg per apartment).

Exclusive:
More heating or cooling effect can be achieved due to the thermal mass inside the building structure.

Heat pump COP

The COP indicates how much extra energy is needed for a heat pump system to provide the required heating or cooling. Based on the former analysis, the heat pump is on only in the cold winter days. Combined with the low-temperature floor heating and underground water storage, the theoretical COP can be calculated by the following formula based on the research of Sabine Jansen[21].

$$\text{COP real} = \eta \times \text{COP Carnot} = \eta \times \frac{T_{design}}{T_{design} - T_{source}}$$

Therefore, with the design temperature of 40 ℃, the underground source temperature of 12 ℃ and the thermal efficiency η of 0.6, the COP can be achieved at 6.7, which means 1 W electrical energy can provide 6.7 W heat for the indoor comfort. Though the practical value might be a bit lower, the heat pump system combined with low-temperature floor heating and geothermal source can reduce lots of energy consumption in terms of indoor comfort.

19. Atul Sharma; V. V. Tyagi; C. R. Chen; D. Buddhi. 2009. "Review on thermal energy storage with phase change materials and applications". Renewable and Sustainable Energy Reviews. 13 (2): 318–345. doi:10.1016/j.rser.2007.10.005

20. https://www.orangeclimate.com/nl/ocautarkis/producten/pcm-klimaatplafonds

21. Sabine Jansen. 2014. Exergy Guidebook for Building Professionals. Version 2. Delft University of Technology. https://klimapedia.nl/publicaties/exergy-for-building-professionals/ p. 47-48

5.3 Primary results

With local climate data, in the coldest hour in winter, the heat demand is 51325.68 W totally (Fig 13). The biggest part of heat loss is ventilation. According to the former calculation, PCMs can provide 37359 W heating. So the extra active heating demand is 13966.68 W.

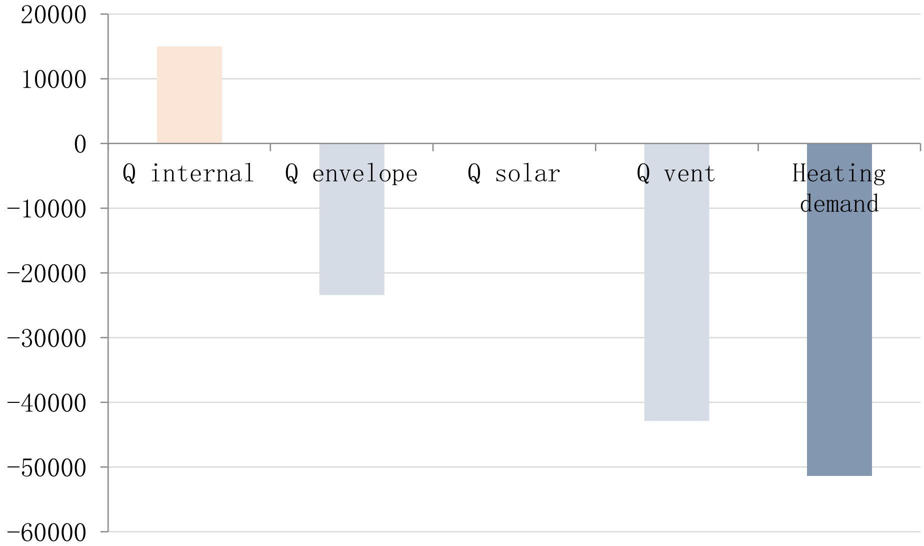


Fig 13 Heat demand for the coldest hour in winter (W)

For the hottest hour in summer, the cooling demand is 58603.32 W totally (Fig 14). The biggest part is solar heat gain, but the difference is not much. Considering the PCM cooling, the extra active cooling demand is 21244.32 W.

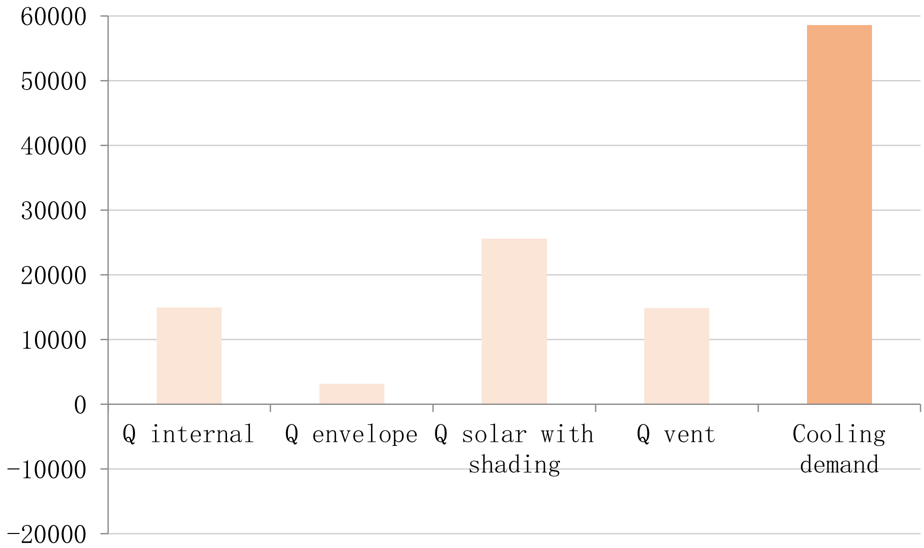


Fig 14 Heat demand for the coldest hour in winter (W)

The hourly results with the extreme condition can be seen in the appendix, which can be used to determine the size of the active heating or cooling equipment.

For the coldest day in winter, the total heating demand is 889499.54 Wh (Fig 15). For the hottest day in summer, the total cooling demand is 122817.65 Wh (Fig 16).

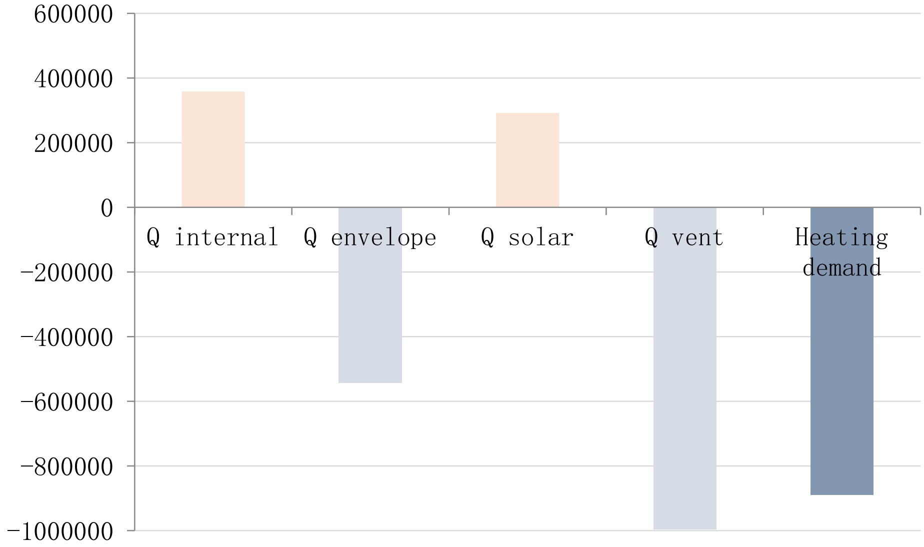


Fig 15 Heat demand for the coldest day in winter (Wh)

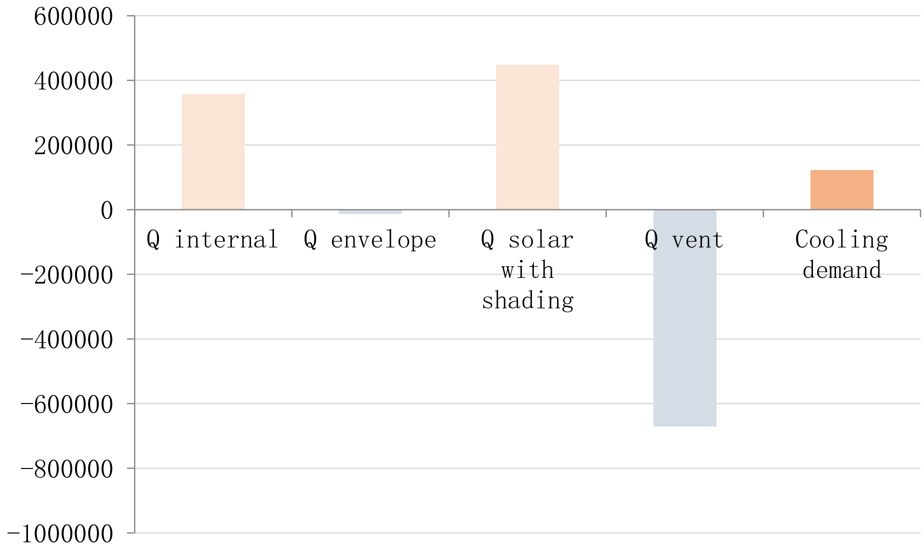


Fig 16 Heat demand for the coldest day in winter (Wh)

The fluctuation between day and night in summer is noteworthy which means a large quantity of cooling is needed just in a short time. Therefore the thermal mass is more efficient in summer than winter. However, the overall demand for heating is bigger than cooling.

5.4 Comparison and optimization

Night ventilation and shading system

Users' behaviour largely influences the result of night ventilation and shading system. In terms of the shading system, the automatic control acts once every three hours while the priority still belongs to users. Night ventilation needs users to open their windows during the night which is not controlled by an automatic system. So in this part, F_{vent} (Table 5 and Fig 17) and $F_{shading}$ (Table 6 and Fig 18)are tested with lower value, which means users are not cooperative as assumed, to see how much influence of users' behaviour could be.

Table 5 comparison of the shading factor in the hottest hour

$F_{shading}$	1	0.5	0.2
Hourly solar heat gain (W)	25601.4	177233.4	268212.6
Hourly cooling demand (W)	58603.32	210235.32	301214.52
Percentage of hourly solar heat gain in total cooling demand (%)	44	84	89

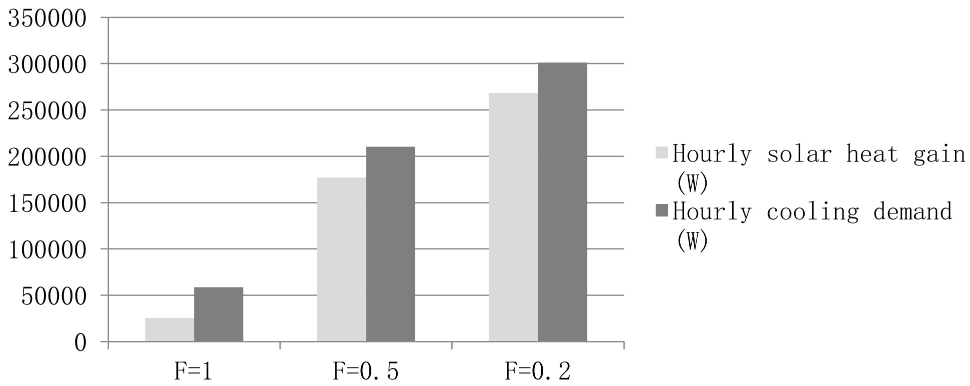


Fig 17 comparison of the shading factor in the hottest hour

Table 6 comparison of the night ventilation factor on the hottest day

F_{vent}	1	0.5	0.2
Daily heat loss via night ventilation (W)	-644436	-322218	-128887.2
Daily cooling demand (W)	122817.65	445035.65	638366.45
Percentage of daily heat loss via night ventilation in total cooling demand (%)	-525	-72	-20

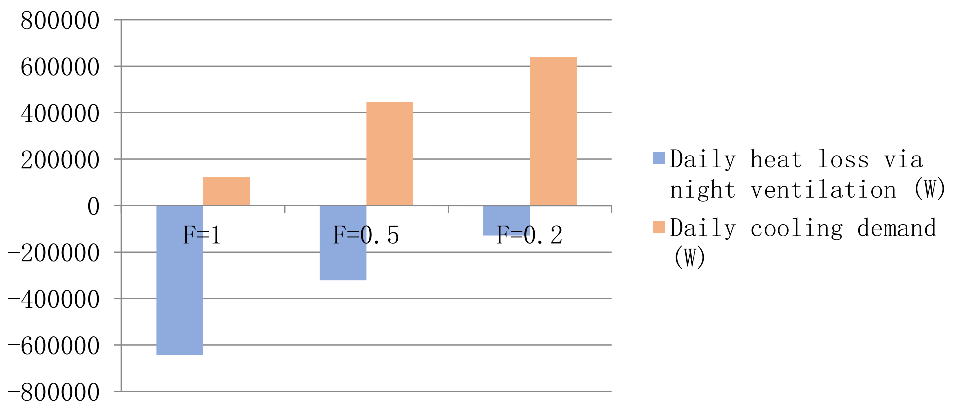


Fig 18 comparison of the night ventilation factor on the hottest day

Based on the result, users' behaviour has a big influence on both half-manually shading system and night ventilation.

U-value of the envelope

The default U-value is quite low which means pretty good insulation performance. The U-value of both glazing façade and closed façade are increased (U_g from 1.1 W/m^{2}K to 1.57 W/m^{2}K, U_{close} from 0.2 W/m^{2}K to 0.5 W/m^{2}K) in this simulation to see the daily result of less good insulation performance.

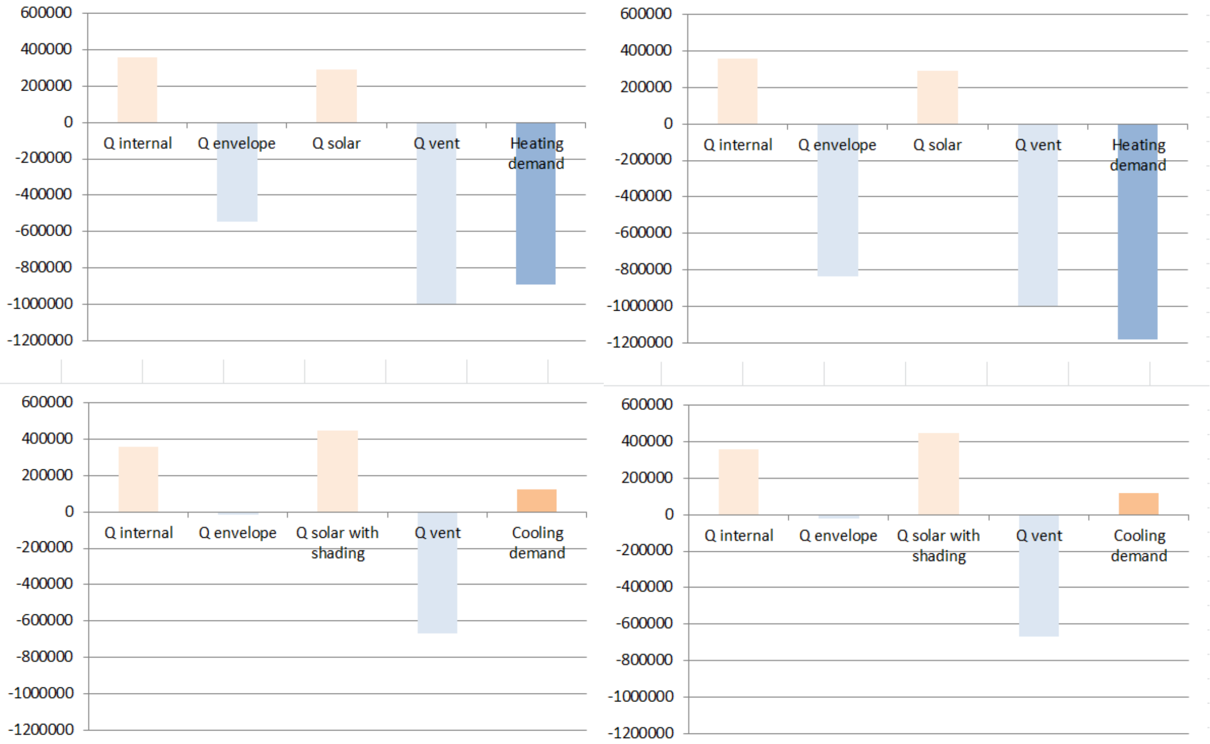


Fig 19 comparison of insulation performance (left: good performance, right: less good performance)

It can be concluded that less good insulation doesn't have a distinct influence for cooling demand, but increases the heating demand largely. Therefore, in the economical range, good insulation performance helps with energy efficiency.

G-value of the glass (g)

Higher solar heat gain which can be achieved by higher G-value is good for winter and adverse for summer. In this simulation, G-value is increased from 0.6 to 0.8 which is proved to achieve a better balance between summer cooling demand and winter heating demand.

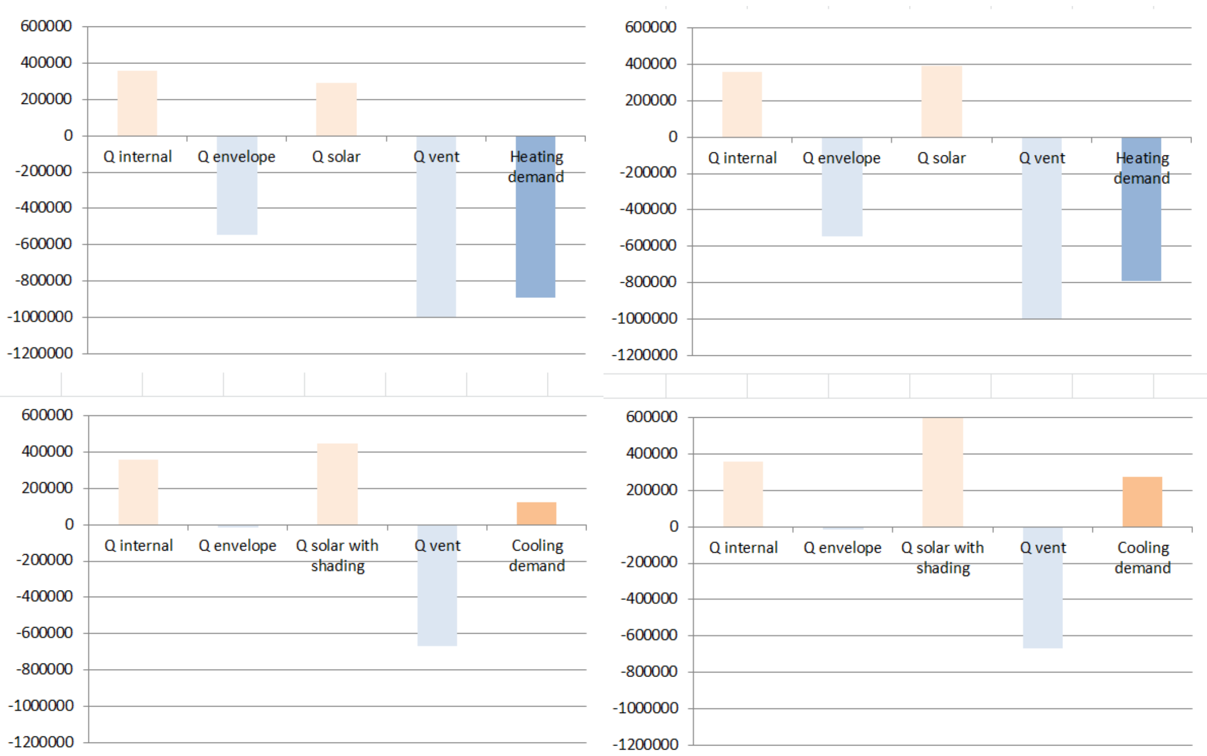


Fig 20 comparison of G-value of the glass (left: G-value = 0.6, right: G-value = 0.8)

Window-to-wall ratio

The change of the northern window-to-wall ratio (WWR_{north} from 0.4 to 0.2) has slight effect on heating (from 889499.54 Wh to 847272.46) and cooling demand (122817.65 Wh to 123916.49 Wh).

In the next simulation (Fig 21), the southern window-to-wall ratio (WWR_{south}) is reduced from 1 to 0.6. The result shows that though lower WWR_{south} only reduced the cooling demand slightly due to the shading system, and doesn't affect the heating demand.

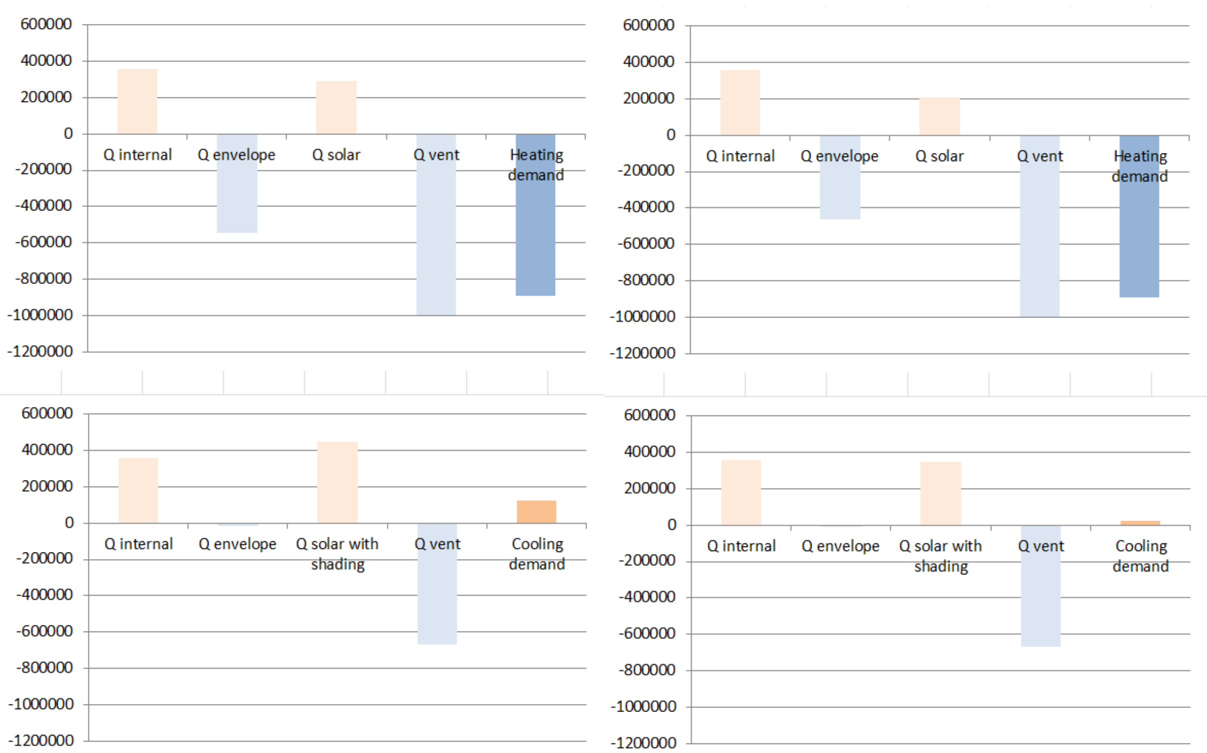


Fig 20 comparison of the southern window-to-wall ratio (left: WWR_{south} =1, right: WWR_{south} = 0.6)

6 CONCLUSION

Based on the analysis of the local climate, the main energy consumption for indoor comfort is heating. Solar heat gain can help during the cool season, however, it is not enough for the heating demand of the coldest period due to the insufficient and unstable solar radiation in winter. So the active heating system is needed. Besides, the cooling demand in the hottest hour should also be taken into consideration. The seasonal differentiation of solar altitude can be used to get solar heat in winter while avoid overheating in summer.

In terms of single living characteristic, the regular time schedule of the working inhabitants make it possible to save energy during the daytime on weekdays, and with small-size studio and floor heating/cooling it possible to achieve indoor comfort in a short time after they come back at night. The shading system could be the combination of users' control and automatic control which means the automatic control acts once every three hours while the priority still belongs to users. The layout inside each studio can be decided and changed by the individual user based on the thermal zone. Sharing a common living room to centralize heating can also help to reduce the energy consumption.

By integrating single energy-efficient technic, several strategies form the foundation of the synergetic system. The combination of the orientation for solar gain (between 150° to 210°) and stack ventilation can fit in the certain urban context, however, the southwest orientation is preferred when possible. Glazing southern façade for solar heat gain need the shading system to avoid overheating in summer. The southern balcony can be a buffer zone, a warm greenhouse, or an ideal outdoor shading terrace under different conditions. Also, by migrating and changing their living environment, inhabitants are more willing to accept wider indoor conditions. The atrium and solar chimney make use of natural airflow and organize the ventilation to reduce heat loss and energy consumption. The atrium can also act as a buffer zone and the sunlight well for northern apartments. Besides the PCMs for heating and cooling, active floor heating and cooling are conducted with the geothermal-source heat pump. Green elements in the atrium can act as absorption of excess solar heat and provide shading in summer.

Based on the strategies and an architectural model, a prototype of the energy-efficient system is established. The operation mode of the system is corresponding to five defined conditions over the year according to the different outside temperature, from cold winter to hot summer. The states of individual elements in the energy-efficient system vary in different condition and collaborate with the whole.

The system is examined and detailed by basic calculation. The primary results of the calculation show that the overall demand for heating is bigger than cooling and the fluctuation between day and night in summer is noteworthy. Therefore the thermal mass can largely improve energy efficiency in summer. Night ventilation can remove 525% heat comparing with total cooling demand in the summer and the shading system can reduce excessive solar heat gain by 80% in the summer to reduce the cooling demand. However, users' behaviour has a big influence in both half-manually shading system and night ventilation. The application of PCMs can provide a considerable amount of heating or cooling. Theoretically, the geothermal-source heat pump with low-temperature floor heating has a coefficient of performance of 6.7.

By testing single parameters, better settings of certain parameters can be concluded. In the economical range, good insulation performance helps with energy efficiency. Higher G-value helps with the balance between summer cooling demand and winter heating demand. With good insulation and shading system, the window-to-wall ratio has little effect on the total heating or cooling demand.

The result of this research is a prototype of an energy-efficient system which can achieve indoor comfort with minimum energy consumption in a single-living residential building in the Netherlands. It gives advice to the design of a sustainable single-living housing project and provides a basic method to analyse and simulate the design decisions and parameters in an energy-efficient system.

BIBLIOGRAPHY

Books

Brown, G. Z, and Mark DeKay. 2013. Sun, Wind, and Light: Architectural Design Strategies. Third [edition] ed. Hoboken: Wiley.

Košir Mitja. 2019. Climate Adaptability of Buildings: Bioclimatic Design in the Light of Climate Change. Cham, Switzerland: Springer.

Nabokov, Peter. 1986. Architecture of Acoma Pueblo: The 1934 Historic American Buildings Survey Project, Historic American Buildings Survey. Santa Fe, NM: Ancient City Press

Remco Looman. 2017. “Climate-Responsive Design: A Framework for an Energy Concept Design-Decision Support Tool for Architects Using Principles of Climate-Responsive Design” 1 (1): 1–282. DOI:10.7480/abe.2017.1.

Papers

Alsaad, Hayder & Chang, Jae. (2014). The Efficiency of Night Insulation Using Aerogel Filled Polycarbonate Panels During the Heating Season. Journal of The Korean Society of Living Environmental System. 21. 570-578. 10.21086/ksles.2014.08.21.4.570.

Atul Sharma; V. V. Tyagi; C. R. Chen; D. Buddhi (February 2009). "Review on thermal energy storage with phase change materials and applications". Renewable and Sustainable Energy Reviews. 13 (2): 318–345. DOI:10.1016/j.rser.2007.10.005

Fitton, R., Swan, W., Hughes, T. et al. Energy Efficiency (2017) 10: 1419. https://doi.org/10.1007/s12053-017-9529-0

Lim B P, Hijazi H, Thiébaux S, et al. 2016. Online HVAC-Aware Occupancy Scheduling with Adaptive Temperature Control[C]. //International Conference on Principles and Practice of Constraint Programming. Springer, Cham. p. 683-700.

Okay Go ̈nu ̈lol, Ayc ̧a Tokuc, Dinçer İbrahim. 2017. Net Zero Energy Residential Building Architecture in the Future. // C. Ozgur Colpan, and Onder Kizilkan, eds. 2018. *Exergetic, Energetic and Environmental Dimensions*. London, England: Academic Press.

Sabine Jansen. 2014. Exergy Guidebook for Building Professionals. Version 2. Delft University of Technology. https://klimapedia.nl/publicaties/exergy-for-building-professionals/

Reports

European Parliament and Council. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union 2010.

WHO. 1988. Guidelines for Healthy Housing. https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012_nvt/artikelsgewijs/hfd9/art9-2

Websites

http://www.soda-pro.com/home

https://www.cbs.nl/nl-nl/nieuws/2018/22/amsterdamse-huishoudens-hebben-minder-woonoppervlakte

https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html

https://www.orangeclimate.com/nl/ocautarkis/producten/pcm-klimaatplafonds

APPENDIX

1. Climate condition

Hourly data

Winter	Local climate data	Extreme condition
Outside temperature	-2 ℃	-10 ℃
Summer	Local climate data	Extreme condition
Outside temperature	28 ℃	35 ℃
Tilted solar radiation	862 W/m2	1000 W
Vertical solar radiation	624 W/m2	800 W

Daily data

Winter (24 hours)	
ΔT_{24h}	-511.1 Kh
Tilted solar radiation	659.9 Wh/ m^2
Vertical solar radiation	730.5 Wh/ m^2
Summer (24 hours)	
ΔT_{24h}	-13.3 Kh
Tilted solar radiation	6611.2 Wh/m^2
Vertical solar radiation	4326.43 Wh/m^2

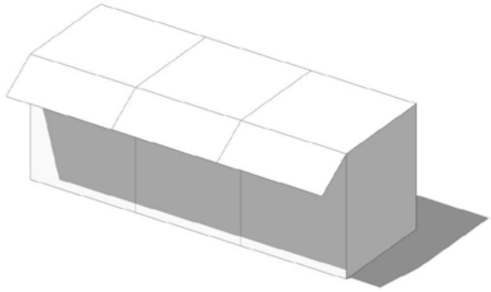
ΔT_{24h} is the accumulation of the difference between outside and inside temperature for 24 hours on the hottest or the coldest day.

Outside T		
t_0		
t_1		
t_2		
t_3		
t_4		
t_5		
t_6		
t_7		
t_8		
t_9		
t_{10}		
t_{11}		
t_{12}		
t_{13}		
t_{14}		
t_{15}		
t_{16}		
t_{17}		
t_{18}		
t_{19}		
t_{20}		
t_{21}		
t_{22}		
t_{23}		

$$\Delta T_{24h} = (t_1 - t_{inside}) + (t_2 - t_{inside}) + (t_3 - t_{inside}) + (t_4 - t_{inside}) + (t_5 - t_{inside}) + (t_6 - t_{inside}) + \cdots + (t_{24} - t_{inside})$$

2. Shading efficiency simulation (orientation: 32.2°SE, location: 51.9°N, 4.48°E)

Hour	1500mm depth	1200mm depth
7.00	0.66	0.52
8.00	0.69	0.56
9.00	0.75	0.6
10.00	0.82	0.66
11.00	0.93	0.76
12.00	1	0.93
13.00	1	1
14.00	1	1
15.00	1	1
16.00	1	1
Average	88.5%	80%

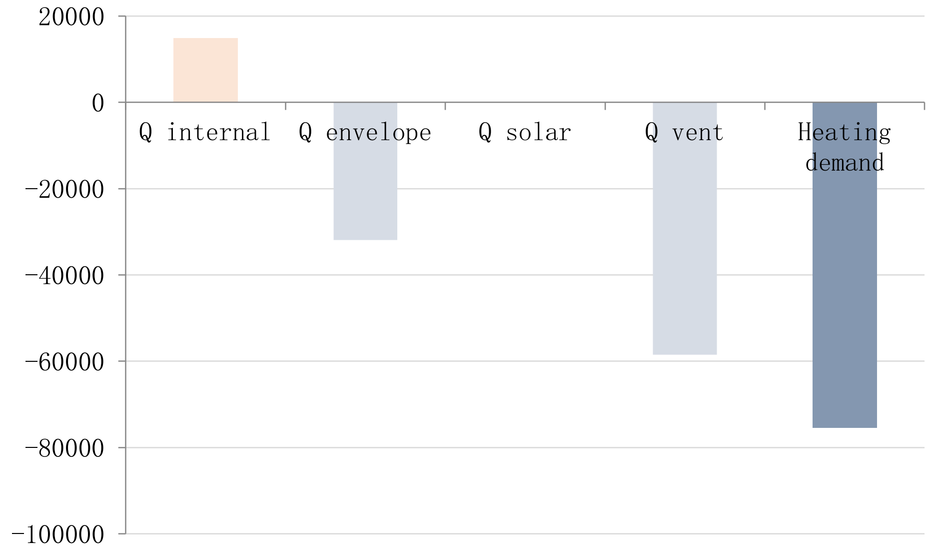


The depth of the shading panel (1200mm and 1500mm) is also compared here. 1200mm seems more efficient.

3. Hourly results with extreme condition

Heating demand in the coldest hour in winter

Q internal	14943.6 W
Q envelope	-31903.2 W
Q solar	0 W
Q vent	-58464 W
Heating demand	-75423 W



Cooling demand in the hottest hour in summer

Q internal	14943.6 W
Q envelope	10634.4 W

Q solar	25601.4 W
Q vent	49560 W
Heating demand	100739.4 W