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Adaptive heating, ventilation and solar shading for dwellings

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ABSTRACT
Calculation of various strategies for the heating of, and the prevention of overheating in, a Dutch standard dwelling that includes (automated) adaptive ventilation systems and solar shading to maintain indoor temperatures at acceptably comfortable temperatures informs this analysis of the costs, impacts and benefits of the use of related control opportunities and mechanisms at play. The energy saving potential of enabling occupants to take advantage of the adaptive opportunities embedded into the dwelling, and discussion of associated cost and benefits of a range of behaviours within the reference dwelling is very high. In the calculations, the total energy saving potential for heating behaviours that take advantage of occupant-driven adaptive behaviours is around 65% of the heating demand for the whole house compared to the saving calculated for the same dwelling controlled by using a standard heating schedule and constant ventilation, which is largely achieved by the use of adaptive controls and fast reaction heating and minimizing ventilation in the heating season. Applying a range of passive cooling strategies, the need for cooling can be eliminated in most situations cancelling the need for the installation of active cooling. It is most effective to use both adaptive ventilation and solar shading.

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Adaptive heating; adaptive ventilation; adaptive solar shading; overheating; energy efficiency; automation; dwellings

Introduction

This article is an excerpt of Chapter 6 of the doctoral thesis 'Adaptive Thermal Comfort Opportunities for Dwellings', providing thermal comfort only when and where needed in dwellings in the Netherlands (Alders 2016). In this dissertation, an inventory has been made of adaptive techniques for thermal comfort to create an adaptive thermal comfort system for dwellings, which is defined as follows:

> the whole of **passive and active comfort components** of the dwelling that **dynamically adapts** its settings to **varying user comfort demands** and **weather conditions** (seasonal, diurnal and hourly depending on the aspects adapted), thus providing comfort **only where, when and at the level needed** by the user, to **improve possibilities of harvesting the environmental energy** (e.g. solar gain and outdoor air) when available and storing it when abundant.

Calculating the full potential of adaptive building characteristics

The dissertation calculates the full energy saving potential for heating and cooling for three different profiles of occupancy and three levels of thermal mass (Table 1) of the following adaptive building characteristics:

F_{sol}: solar factor of facade ($q_{rad,gain}/q_{rad,inc}$) – the portion of radiation falling on the entire facade that enters the room as heat

H_{tot} (W/K): total heat transfer coefficient ($H_{ve} + H_{tr}$) – the total heat loss from indoor air to outdoor air per K temperature difference by ventilation and transmission.

Furthermore, the actual thermal comfort demand is determined in time and place to be able to provide heating and cooling only when and where needed according to the definition of the Adaptive Thermal Comfort System. The calculated variants of control are given in Table 2. The values mentioned below are based on the proportions of the reference dwelling of AgentschapNL and in the Dutch climate. These calculations are based on generic physical properties that are regarded to be disconnected (e.g. adapting the glass percentage for the solar factor has no influence on the transmission properties of the facade) to be able to isolate the individual parameters in order to encourage development of new concepts for materials and techniques.

Energy saving potential

Above the energy saving of adaptive heating and minimizing the heat loss factor by high insulation values and ventilation controlled by presence the adaptive approach offers the possibility of increasing the solar gain without causing overheating. This significant amount of energy saving can only be obtained in the theoretical case if the solar factor can be disconnected from the heat loss factor and a 100% of the solar radiation hitting the facade can be used as heat gain ($f_{sol} = 1$). It should be noted that the ultimate energy saving potential for heating and cooling can be higher if there is some form of prediction by an Adaptive Model Predictive Control (Oldewurtel et al. 2012) with anticipation of future comfort demand to prevent the indoor temperature to drop below heating set point at absence due to passive cooling.

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Table 1. Calculated cases.

Thermal mass level			Capacitance (J/km^2) (per m^2 floor area)		
Low			80.000		
Middle			165.000		
High			370.000		
Year					
2050 W+			Test reference year by TNO (NEN_5060 2008)		
Room			**Volume (m^3)**		
Living room			85		
Bedroom			42		
Occupancy profiles	**Code**	**People in household**	**Occupancy rate (%)**	**Average number of people present**	**Average activity level**
One student	1st	1	10	1.26	2.5
Couple both with job	2w	2	18	1.32	2.1
Couple with 2 small children	4sm	4	46	1.70	2.4

Table 2. Calculated control variants.

	Control $\Phi_{HC,nd}$		Control H_{tot}					Control f_{sol}		
Variants	Timing	Set point	Automation	Frequency	Range U_{opaque} (W/m^{2}K)	Range U_{tr} (W/m^{2}K)	Range Q_{ve} (1/h)	Automation	Frequency	Range f_{sol}
Reference	s	hi/lo	–	–	0.2	1.6	1.25	–	–	0.6*f_{glass}
Adaptive heating	p	ACA	–	–	0.2	1.6	1.25	–	–	0.6*f_{glass}
Max heat loss	p	ACA	–	–	0.2	1.6	30	–	–	0
Min heat loss	p	ACA	–	–	0.1	1.2	min$_{pres}$	–	–	1
Adaptive $H_{tot,hour}$	p	ACA	+	h	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	–	0.6*f_{glass}
Adaptive $H_{tot,day}$	P	ACA	+	d	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	–	0.6*f_{glass}
Adaptive $H_{tot,season}$	P	ACA	+	s	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	–	0.6*f_{glass}
Adaptive $H_{tot,month}$	P	ACA	+	m	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	–	0.6*f_{glass}
Presence $H_{tot,hour}$	P	ACA	–	h	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	–	0.6*f_{glass}
Adaptive $f_{sol,hour}$	P	ACA	–	–	0.2	1.6	min$_{pres}$	+	h	0–1
Adaptive $f_{sol,day}$	P	ACA	–	–	0.2	1.6	min$_{pres}$	+	d	0–1
Adaptive $f_{sol,season}$	P	ACA	–	–	0.2	1.6	min$_{pres}$	+	s	0–1
Adaptive $f_{sol,month}$	P	ACA	–	–	0.2	1.6	min$_{pres}$	+	m	0–1
Presence $f_{sol,hour}$	P	ACA	–	–	0.2	1.6	min$_{pres}$	–	h	0–1
ad $H_{tot,hour}f_{sol,hour}$	P	ACA	+	h	0.1–0.2	1.2–1.6	min$_{pres}$-30	+	h	0–1
ad $H_{tot,day}f_{sol,day}$	P	ACA	+	d	0.1–0.2	1.2–1.6	min$_{pres}$-30	+	d	0–1
ad $H_{tot,season}f_{sol,season}$	P	ACA	+	s	0.1–0.2	1.2–1.6	min$_{pres}$-30	+	s	0–1
ad $H_{tot,month}f_{sol,month}$	P	ACA	+	m	0.1–0.2	1.2–1.6	min$_{pres}$-30	+	m	0–1
pres $H_{tot,hour}f_{sol,hour}$	P	ACA	–	h	0.1–0.2	1.2–1.6	min$_{pres}$-30	–	h	0–1

s, Standard heating schedule; p, presence; hi/lo, set point (21°C) and setback (15°C); ACA, Adaptive Comfort Algorithm (Peeters et al. 2009); –, none; +, automation; H, hourly switch; d, daily switch; s, seasonally switch; m, monthly switch; f_{glass}, percentage of glass in facade.

Cooling

Applying the variable building characteristics as described in the thesis, the cooling can be eliminated in most situations and will be 10% of the initial value at most. The remaining cooling demand will be low enough to cancel the need for installation of active cooling. It is most effective to use both an adaptive heat loss factor and solar factor; however, of the two the solar factor is most effective.

The energy saving potentials of the separate solutions are given in Table 3. The total energy saving potential of the added measures is therefore mentioned in the bottom of Table 3. To increase the thermal storage a PCM or a dynamic thermal storage (HATS) (Hoes 2014) could be applied.

Required values for H_{tot} and f_{sol}

The energy saving potential calculated in the thesis is based on theoretical values for the ranges of the H_{tot} and f_{sol} in a more or less realistic but theoretical range; consequently, the actual energy saving potential can vary according to the actual ranges of the variable building characteristics. Varying the heat loss factor is more feasible with increasing the ventilation because this can more easily reach very high heat loss factors. Developing new techniques for increasing the heat loss factor by transmission is only competitive to ventilation if high conductive properties can be incorporated in new materials or techniques.

In this study, it is shown that the advantage of increasing the solar gain in the heating season is significant. However, varying the solar factor between the values assumed in the calculations from 0 to 1 is not possible with current techniques. Blocking all solar radiation is difficult without blocking all vision out and glazing will always block a percentage of the heat, making it impossible to reach the value of 1 by currently available materials. New techniques could include new materials for advanced radiation transfer or harvesting more solar radiation by increasing the surface of incidence such as applying solar collectors.

Effect of the thermal mass

The most important conclusion about thermal mass in these calculations is that the control of the heat loss factor and the solar factor is significantly more stable with the higher thermal mass. The application of passive cooling by increasing the heat loss factor and/or decreasing the solar gain in case of low thermal mass

Table 3. Summary of energy saving potential of the Adaptive Thermal Comfort System based on the generic calculations.

		4sm		2w		1st		Average	
		Living room	Bedroom	Living room	Bedroom	Living room	Bedroom	Living room	Bedroom
Adaptive heating	Energy saving potential[a]								
	Heating	12%–23%	17%–20%	37%–48%	16%–19%	41%–47%	13%–14%	34%	16%
	Overheating	–	–	–	–	–	–	–	–
Minimized heat loss	ACPH (1/h) = 0.5 + 0.2*p				Rc_{op} [km²/W] = 10			U_w [W/km²] = 1.2	
	Energy saving potential[a]								
	Heating	67%–74%	87%–93%	64%–65%	88%–94%	63%–65%	86%–92%	66%	90%
	Overheating[b]	–	–	–	–	–	–	–	–
Adaptive heat loss	ACPH (1/h) = 0.5 + 0.2*p				Rc_{op} [km²/W] = 2.5–10			U_w [W/km²] = 1.2–2.5	
	Energy saving potential[a,c] (*)								
	Heating[d]	−5% to 0%	−2% to 0%	−1% to 0%	−3% to 0%!!	−1% 0%!!	−2% to 0%!!	−1%	−1%
	Automated[e]	**3%–32%**	**1%–12%**	**1%–7%**	**0%–15%**	**1%–8%**	**0%–6%**	9%	6%
	Overheating	74%–95%	78%–98%	73%–95%	87%–98%	70%–94%	83%–98%	84%	92%
	Automated[e]	**5%–9%**	**1%–11%**	**22%–25%**	**0%–11%**	**35%–38%**	**1%–14%**	22%	6%
Adaptive solar factor		F_c					0–1		
	Energy saving potential[a,f] (*)								
	Heating[d]	33%–83%	69%–100%	53%–81%	72%–100%	48%–81%	66%–93%	63%	83%
	Automated[e]	**36%–52%**	**96%–100%**	**49%–68%**	**72%–99%**	**46%–74%**	**66%–90%**	54%	83%
	Overheating	97%–100%	92%–96%	99%–100%	91%–95%	99%–100%	96%–98%	99%	95%
	Automated[e]	**15%–21%**	**96%–92%**	**67%–74%**	**90%–94%**	**76%–82%**	**93%–95%**	56%	93%
ACTS	Energy saving potential[a,g]								
	Heating	27%–82%	99%–100%	50%–80%	99%–100%	44%–81%	99%–100%	61%	99%
	Automated[e]	**36%–50%**	**101%–114%**	**50%–68%**	**100%–117%**	**49%–74%**	**97%–105%**	55%	105%
	Overheating	98%–100%	100%	99%–100%	100%	100%	100%	100%	100%
	Automated[e]	**2%–7%**	**3%–24%**	**20%–43%**	**2%–23%**	**33%–59%**	**2%–28%**		

[a]These values are based on the generic calculations of the thesis (Alders 2016) and are based on the reference dwelling of AgentschapNL. The variation in energy saving potential per situation depends on the thermal mass level.
[b]Overheating escalates without additional measures in summer.
[c]For the energy saving potential on cooling by adaptive heat loss coefficient this amount depends on the thermal mass level and (less) on the level of maximum heat loss coefficient.
[d]Heating can be increased by lack of prediction and thermal storage.
[e]Automated control; shows the added energy saving of automated control above non-automated control.
[f]The energy saving potential of the f_{sol} for heating is due to the maximization of the solar gain in the heating season.
[g]The total energy saving potential of all discussed measures compared to the reference situation with average insulation, average solar factor and constant ventilation [1.25 1//h].
–, Not applicable.

leads to an increase in heating demand due to the temperature drop during absence.

In the reference cases the cooling load is significantly lower for higher thermal mass and the heating load does not significantly vary with thermal mass due to the good basic insulation of the dwelling and sufficient solar gain. The energy saving for cooling by the adaptive strategies is higher with high thermal mass more drastically reducing the already much lower cooling demand for higher thermal mass. This can be explained by the fact that the thermal mass causes the heat to be lost to spread more evenly amongst the hours, which means the peaks for heat to be discarded will be much lower.

In case of the North orientation, it can be an option to build with lower thermal mass especially if there is no increase of solar gain available because the solar radiation has significantly less effect on the heating demand, showing a slight increase in heating demand for higher thermal mass.

Effect of occupancy

The control of the thermal comfort system according to the occupancy and the resulting comfort demand is an essential part of the Adaptive Thermal Comfort System as the definition suggests. The difference between the energy saving is apparent in the case of adaptive heating, where high occupancy means less heating demand if a standard heating schedule is used because of higher internal gain the heating demand with control for presence shows less deviation between the occupancy profiles. This means that the energy saving is larger with lower occupancy level. Furthermore, the control algorithms are significantly less accurate in case of the occupancy profile 4_sm with high occupancy. This effect decreases with higher thermal mass because of the slower temperature decrease.

Additionally, the occupancy has a great effect on the effectiveness of non-automated systems in case of overheating prevention. This emphasizes the need for automated overheating protection by especially solar shading in case of larger periods of absence during the day.

Heat up and cool-down speed

Heat up and cooling down speed are important characteristics of heating systems. In these calculations, it is assumed that the heating power is unlimited and there is no limit to the speed. However, the calculated required heat up speed is largely in a practical range especially if the temperature is stabilized around the comfort temperature by thermal mass, insulation and the adaptive heat loss factor and solar factor. Nevertheless, heat up and cool-down speed are serious considerations for the concept of adaptive heating.

Table 4. Summary of occupancy characteristics of occupancy profiles to be used in the calculations

		LIVING ROOM			KITCHEN			MASTER BEDROOM			BEDROOM 2 /OFFICE			BEDROOM 3			
	Characteristic	Occupancy rate [%]	Average occupancy	Average activity	Occupancy rate [%]	Average occupancy	Average activity	Occupancy rate [%]	Average occupancy	Average activity	Occupancy rate [%]	Average occupancy	Average activity	Occupancy rate [%]	Average occupancy	Average activity	Not at home [%]
profile	Composition																
1_st	1 person household, student	10	1.26	2.5	2	1	3.25	33	1	1	8	1	2	–	–	–	53
1_soc	1 person household, social with much visit	17	1.19	2.0	11	1	3.30	34	1	1	17	1	2	–	–	–	6
2_h	2 person household, at least one with work from home or no job	54	1.35	2.0	14	1	3.45	62	1.39	1	54	1	2	–	–	–	0
2_w	2 person household, both with job	18	1.32	2.1	8	1	3.25	39	1.73	1	1	1	2	–	–	–	41
4_sc	4 person household, school going children	30	1.69	2.0	8	1.55	3.70	40	1.81	1	30	1	1	46	1	1	28
4_sm	4 person household, two children under the age of 5	46	1.70	2.4	15	1.35	3.20	37	1.77	1	43	1	1	34	1	1	16

*household types based on the household types reported in the Time Use Survey (NIWI 2002)
NIWI. 2002. "Tijdsbestedingsonderzoek 2000 TBO'2000." In.: Netherlands Institute for Scientific Information Services.

Practical solutions for standard housing in the Netherlands

In the previous section for both the solar factor (f_{sol}) and the specific heat loss coefficient (H_{tot}) optimal ranges and switching frequencies have been found and the full energy saving potential is very large. However, the approach was to disconnect their characteristics from (existing) techniques not to be hindered by technical limitations beforehand. In this paper, the techniques of the inventory for adaptive techniques made in the dissertation are linked to the conclusions of the generic physical calculations to be translated to practical concepts and constraints for these concepts. Some of the concepts are evaluated for applicability and efficiency in a Reference Dwelling of AgentschapNL in various occupancy scenarios and with high and low thermal mass. It reconnects the previous conclusions to design practice and gives guidelines how to design an Adaptive Thermal Comfort System.

Researched concepts for a standard Dutch dwelling (reference dwelling of AgentschapNL)

Context: the occupant

The dwelling of the example concepts will be a family home which can be occupied by an undetermined family. The calculations to assess the energy saving potential of the Adaptive Thermal Comfort System will be made with the same three occupant profiles used in the generic calculations with the occupancy profiles and characteristics as shown in Table 4 derived from a Time Use Survey conducted by CBS (NIWI 2002). In this example concept, the spatial layout of the attached reference dwelling by AgentschapNL (DGMR 2006) is calculated, which is regarded as a standard Dutch dwelling. Figure 1 shows the floor plans of this dwelling. The living room is oriented South and has large windows to be able to optimally allow in or block solar radiation. The bedrooms are oriented South or North and have smaller windows. Figure 2 shows the facades of the dwelling.

Context: the weather

The dwelling for the example concepts will be situated in the Netherlands, which has a dominant heating demand (in winter). However, as concluded in the thesis the summers are hot and sunny enough to cause overheating problems if the dwelling is designed to predominantly save heating energy by insulating the dwelling very well without extra measures in summer. Figure 3 shows a summary of the incoming solar radiation per month for the reference dwelling of AgentschapNL (DGMR 2006) oriented with the back facade to the South and the maximum, average and minimum ambient temperature per month for the test reference year of 2050 W+ (NEN_5060 2008; KNMI 2014).

Adaptive solar shading

In the example, with a *G*-value of the glass of 0.6 (HR++), the maximum range of solar factor for the South facade of the living room is 45–0%. For the rest of the facades this is 25–0%. In the TRNSYS simulation, the f_{sol} of the North facade will be varied; however, it is expected not to have much effect because

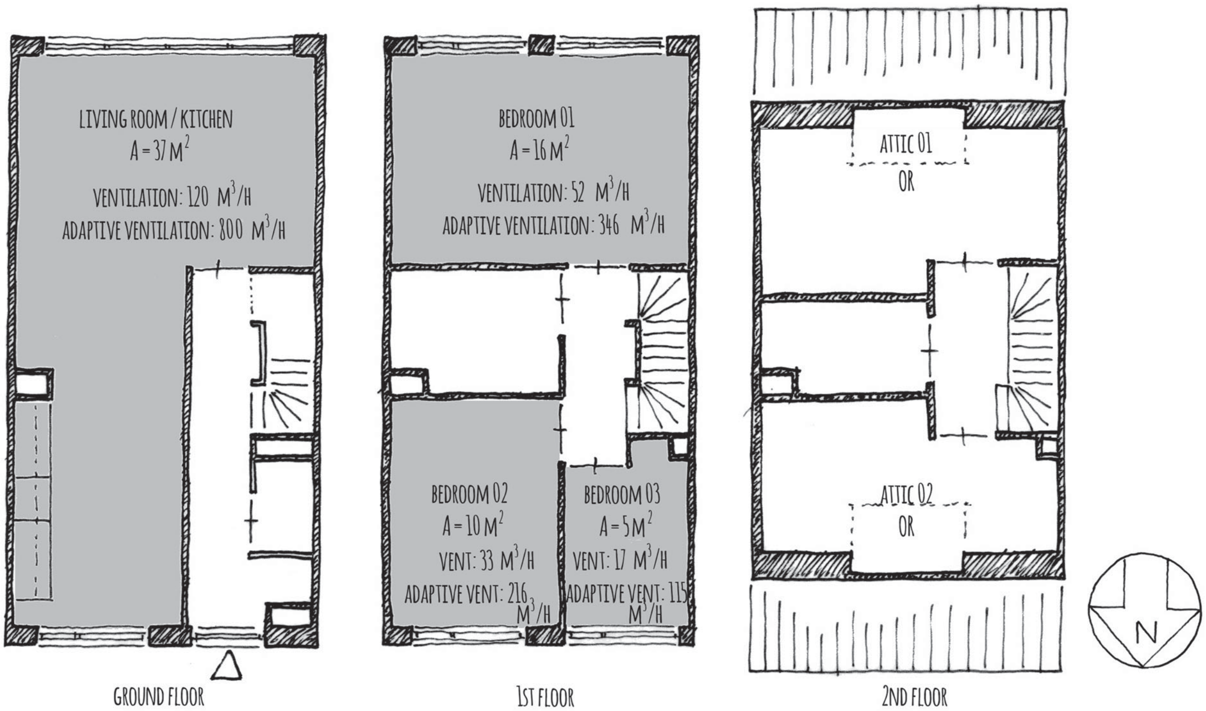


Figure 1. Floor plans of dwelling used for case study.

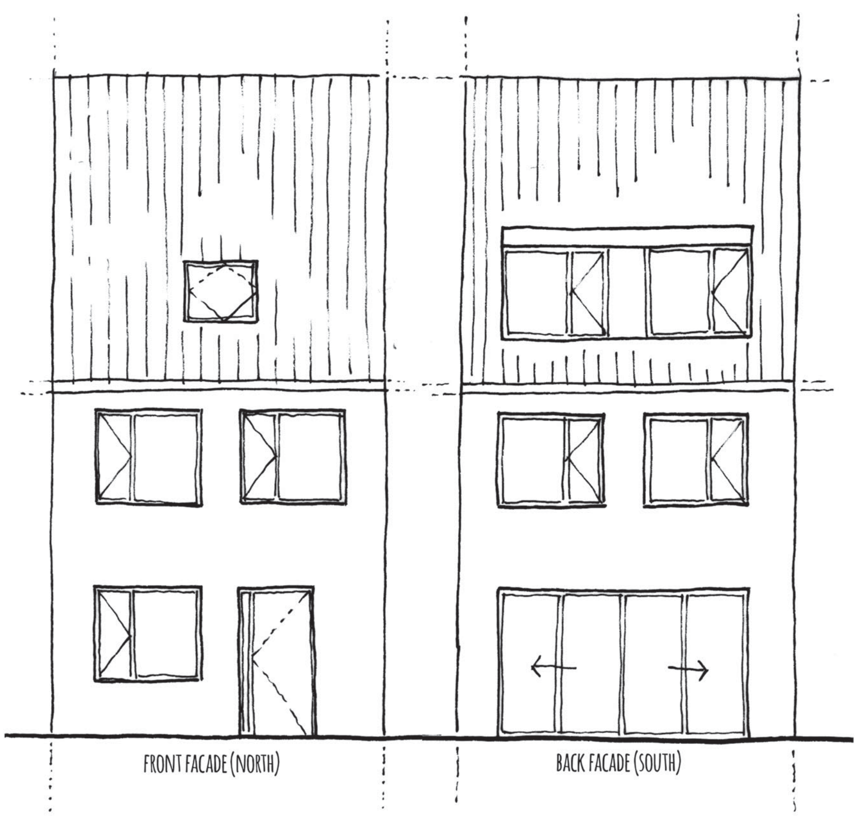


Figure 2. Facades of dwelling used for case study.

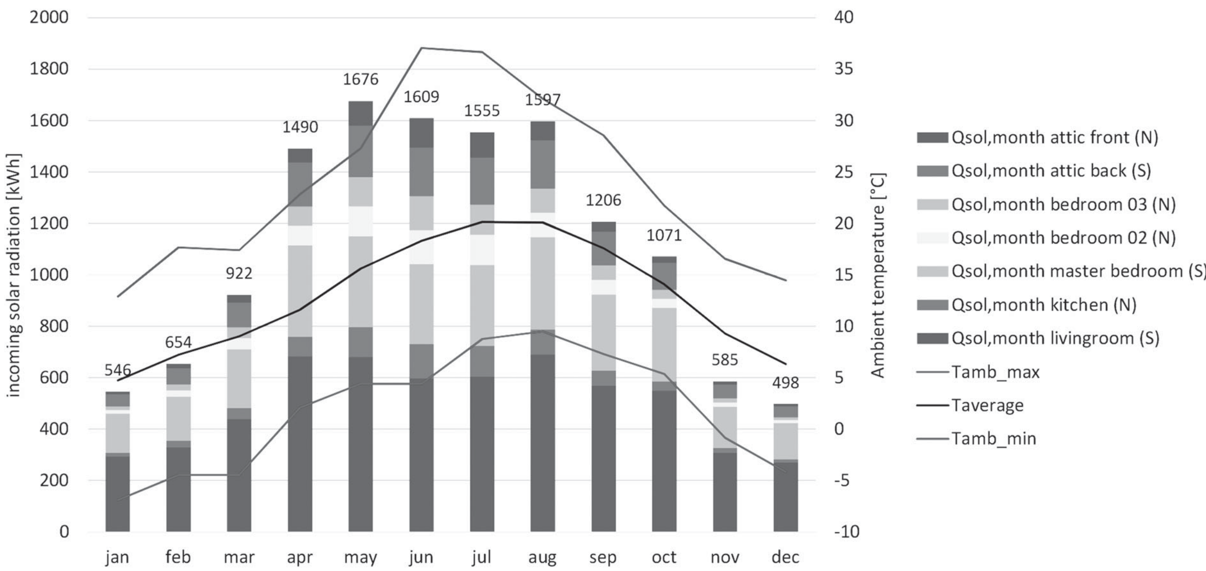


Figure 3. Incoming solar radiation through the windows for the whole house together with the average ambient temperature per month (2050 W+).

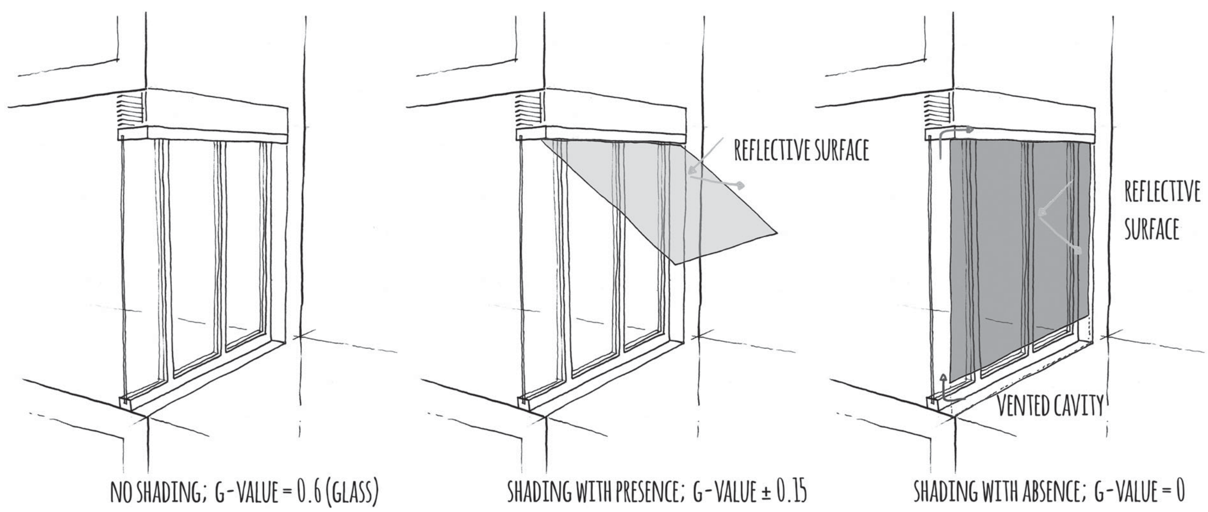


Figure 4. Concept for varying the f_{sol} combined screens and awnings.

of the little solar radiation during the summer season. A combination between screens and controllable awnings is chosen in the form of awnings with a reflective surface on the outside that can also be placed parallel to the glass with a cavity that can be vented to prevent overheating of the screen (Figure 4). With this solution (otherwise it will be completely dark when people are home) it is possible to reach the maximum range for solar shading; however, it should be noted that with this setting, also the visual light and view out are blocked. In practice this might not be desirable. However, the beam radiation can be blocked and shading values of 0.15 can easily be reached with the awning setting. Therefore, during presence the maximum solar shading will be a *G*-value of 0.15. Furthermore, when the screen is parallel to the glass, a cavity between the glass and the screen should be created to ventilate the heat from the surface of the screen that will be heated up by the sun, to make sure no significant solar radiation will 'leak' into the space.

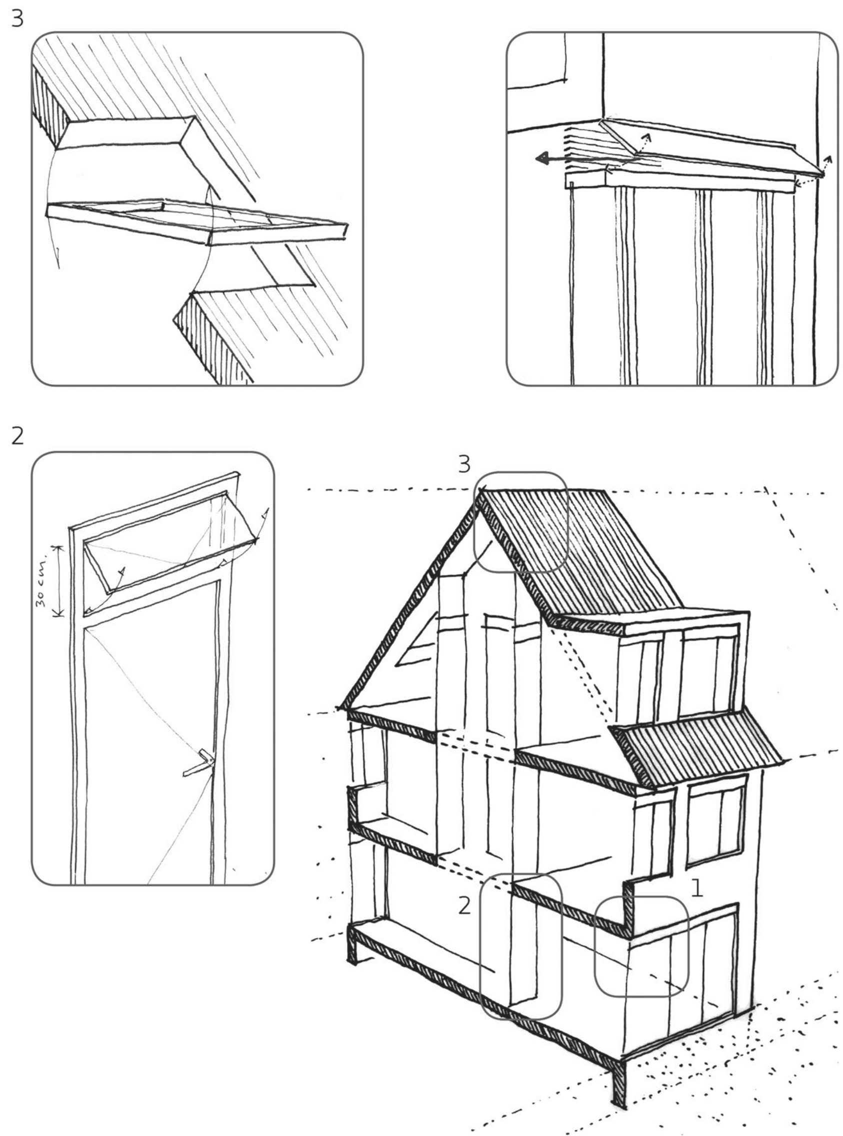
Adaptive ventilation

For the ventilation for temperature control, considerable openings should be present, as shown in the example in Figure 5, which will be simulated in the TRNSYS variants for assessment. The control strategies for natural ventilation assessed in the example concepts are:

- Pressure controlled inlet (constant inlet flow, exhaust controlled mechanically)
- CO_2 controlled ventilation (minimal ventilation, exhaust controlled mechanically)
- Temperature and CO_2 controlled ventilation (minimal ventilation, exhaust controlled mechanically)

Thermal mass

In general, it is preferred to build in high thermal mass as also becomes clear from the previous calculations. In the example, two levels of thermal mass will be researched: low and high to



1: Vents above windows of 30 cm height controlled for adaptive ventilation for passive cooling

2: Vents above internal doors of 30cm height opened together with vents above windows in the corresponding roomto enhance airflow through the building

3: Rooflight in staircase opened with either window vent in the house to enhance airflow through the building

Figure 5. Concept for varying the natural ventilation for passive cooling by purge ventilation in the TRNSYS simulations (combined with base minimized ventilation natural supply, mechanical exhaust).

reassess the influence of the thermal mass on the performance of the Adaptive Thermal Comfort System (Table 5).

Simulated variants

The design example is calculated in TRNSYS with the different cases (Table 5) and the control variants shown in Table 6. The overheating is measured in degree hours above cooling set point. At presence, this is the upper limit of the comfort bandwidth and at absence, this is 30°C. The design will be regarded as a whole house and all the performances of the rooms will be summed or averaged.

Energy use of the reference situations

First, the reference situations for all combinations of all cases are calculated, with assumptions shown below in Table 7.

Figure 6 shows the annual heating demand for each combination of occupancy profile and thermal mass variant together with the distribution of that energy demand over the months of the year. Figure 7 shows the overheating in degree hours. The overheating numbers in the graphs are the average of overheating degree hours of all used rooms in the occupancy profiles. In the two-person household the second bedroom is used sparsely and the third bedroom is unused. In the one-person household both the second and third bedrooms are unused.

Table 5. Calculated cases in TRNSYS.

CASES					
Thermal mass				Capacitance (kg/m^2) (per floor area)	
Low				80.000	
High				370.000	
Year					
2050 W+				Test reference year, warm	
Occupancy profiles	Code	People in household	Occupancy rate	Average amount of people present	Average activity level
1 student	1st	1	10%	1.26	2.5
Couple both with job	2w	2	18%	1.32	2.1
Couple with 2 small children	4sm	4	46%	1.70	2.4

Table 6. Calculated control variants in TRNSYS.

Control variants (all variants except for the presence controlled variants (e&f) are calculated with natural ventilation supply as well as with mechanical ventilation supply with heat recovery)		Heating and cooling		Ventilation				Shading	
Variant	Code	s/p	hi-lo/ACA	+/−	a/p	Base ventilation rate (1/h)	0/1	a/p	0/1
Reference	1_ref	s	hi/lo	+	–	1.25	0	–	0
Adaptive heating	1a_ref	p	ACA	+	–	1.25	0	–	0
Minimized ventilation	1b_ref	p	ACA	+	–	min$_{pres}$	0	–	0
Minimized ventilation nc	1c_ref	p	ACA	–	–	min$_{pres}$	0	–	0
Adaptive ventilation	2b_ventdyn	p	ACA	+	a	min$_{pres}$	0–1	–	0
Adaptive ventilation nc	2c_ventdyn	p	ACA	–	a	min$_{pres}$	0–1	–	0
Presence ventilation	2e_ventdyn	p	ACA	+	p	min$_{pres}$	0–1	–	0
Presence ventilation nc	2f_ventdyn	p	ACA	–	p	min$_{pres}$	0–1	–	0
Adaptive ventilation	3b_soldyn	p	ACA	+	–	min$_{pres}$	0	a	0–1
Adaptive ventilation nc	3c_soldyn	p	ACA	–	–	min$_{pres}$	0	a	0–1
Presence ventilation	3e_soldyn	p	ACA	+	–	min$_{pres}$	0	p	0–1
Presence ventilation nc	3f_soldyn	p	ACA	–	–	min$_{pres}$	0	p	0–1
Adaptive ventilation	4b_dyn	p	ACA	+	a	min$_{pres}$	0–1	a	0–1
Adaptive ventilation nc	4c_dyn	p	ACA	–	a	min$_{pres}$	0–1	a	0–1
Presence ventilation	4e_dyn	p	ACA	+	p	min$_{pres}$	0–1	p	0–1
Presence ventilation nc	4f_dyn	p	ACA	–	p	min$_{pres}$	0–1	p	0–1

s/p, s = standard heating schedule/p = presence controlled (adaptive heating); hi-lo/ACA, hi-lo = set point and setback/ACA Adaptive Comfort Algorithm (Peeters et al. 2009); +/−, + = cooling/−- = no cooling, calculating overheating in degree hours; a/p, a = adaptive control (automated)/p = operated with presence (non-automated); 0/1 (ventilation), 0 = no extra ventilation/0–1 = extra ventilation on or off; 0/1 (shading), 0 = no solar shading/0–1 = shading on or off.

Table 7. Initial values for the reference situations.

INITIAL VALUES		
Operation		
Ventilation (1/h)	1.25	(0.9 l/sm^2)
Schedule living room	**Heating set point (°C)**	**Cooling set point (°C)**
0:00–6:00	15	30
6:00–23:00	20.5	25
13:00–0:00	15	30
Boundary	**Heating set point (°C)**	**Cooling set point (°C)**
0:00–6:00	18	25
6:00–23:00	15	30
13:00–0:00	18	25
Boundary	**Equipment (W/m^2)**	**People (W)**
Absence (occupancy schedule)	1	–
Presence (occupancy schedule)	10	75 * (amount of people)

The heating demand does not vary much between high thermal mass and low thermal mass in Figure 6 and is slightly higher for the low thermal. Furthermore, the heating is significantly higher the lower the occupancy pattern, which is caused by the equal heating hours for each profile but more internal gain for the profiles with higher occupancy.

The overheating is significantly higher for lower thermal mass and significantly higher for higher occupancy rates, as Figure 7 shows. The rooms that are not used in the profiles show no overheating degree hours because the hours are only measured at presence.

Results and discussion

Adaptive heating

The next step is researching the energy saving potential for adaptive heating; providing heating only when and where needed at the level needed as opposed to fixed day and night temperatures. The comfort temperature will be calculated by the adaptive comfort algorithm method and the heating will only function at the presence of the occupants or if the temperature falls below the setback temperature of 15°C. In practice, the temperature will never fall below this 15°C because the insulation is high enough to prevent this. Figure 8 shows the energy saving potential for adaptive heating compared to the reference situation; absolute yearly energy consumption (kWh) for adaptive heating and relative to the reference situation with scheduled heating (%). Figure 9 shows the overheating in degree hours absolute and relative to the reference situation (Figures 6 and 7). The overheating numbers in the table are the average of overheating degree hours of all used rooms in the occupancy

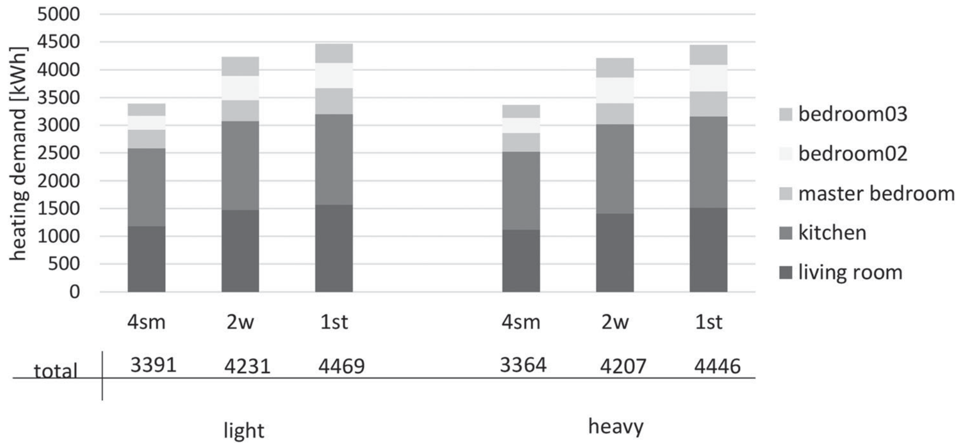


Figure 6. Energy use for heating in kWh in the whole house in the reference situations with fixed ventilation and day and night setting for heating.

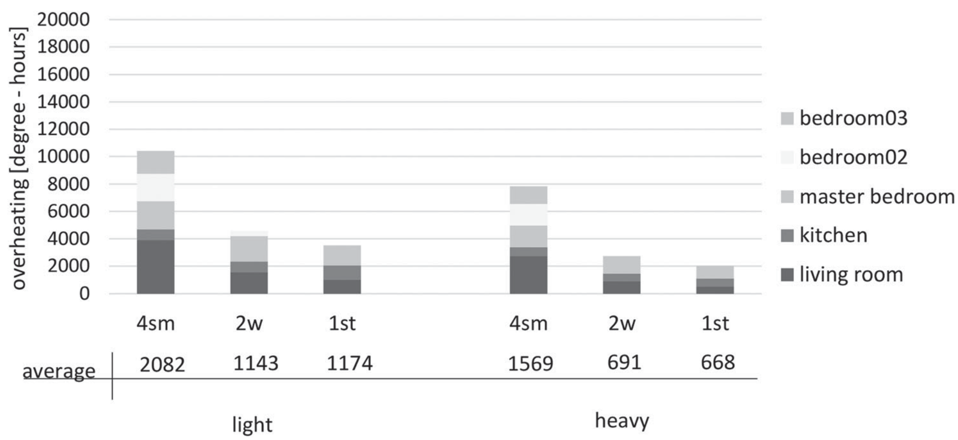


Figure 7. Overheating in degree hours in the whole house in the reference situations with fixed ventilation and day and night setting for heating.

profiles. It should be noted that in the simulations it is assumed that the heating and cooling power is unlimited and has a response time equal to the calculated time step. This means that inertia of the heating delivery system by its thermal mass is not regarded. Systems in practice could therefore be less effective the slower they are.

As becomes clear by Figure 8, adaptive heating can achieve a significantly better energy performance for the whole house. The energy saving is very little (around 5%) for the family with two children (4sm) because their occupancy profile mostly resembles the standard heating times set by the thermostat and the one-person household with the lowest occupancy rate and the least people in the household can gain almost 40% energy saving by the adaptive approach, which is a similar amount. The overheating (Figure 9) is similar to the reference situation showing a slight decrease in the light variant. This is because extra heating can cause a slight cooling demand later on depending on the occupancy of the rooms and incoming (extra) heat by solar radiation. It is remarkable that the rooms that are not in use still show a heating demand. This can be explained by the fact that the heating set point at absence in every room is still 15°C as opposed to 16–180°C at presence in the bedrooms and the ventilation is standardized at an ACPH of 1.25 1/h, which is quite high.

Minimized ventilation

The energy saving for heating by minimizing the ventilation is calculated taking into account the fact that this significantly increases overheating. Figure 10 shows the absolute energy consumption (kWh) for heating by minimized ventilation and relative to the situation of adaptive heating (%) and Figure 11 shows the overheating in degree hours above cooling set point in house reference situations with minimized ventilation. The overheating numbers in the table are the average of overheating degree hours of all used rooms in the occupancy profiles.

From Figure 10, it can be concluded that the energy saving of minimizing the ventilation in the heating season is very effective (almost 50%) and most effective with the most heating hours, which is the case of the profile with the couple with two children (4sm) in addition to the energy saving by adaptive heating. It is now noticeable that the unoccupied bedroom shows a higher decrease in heating demand than the living room, kitchen and the master bedroom because now the ventilation is always low at an ACPH of 0.5 1/h.

However, Figure 11 shows that the overheating problems are significant if no counteractions are taken. This problem aggravates with rising occupancy because the overheating degree

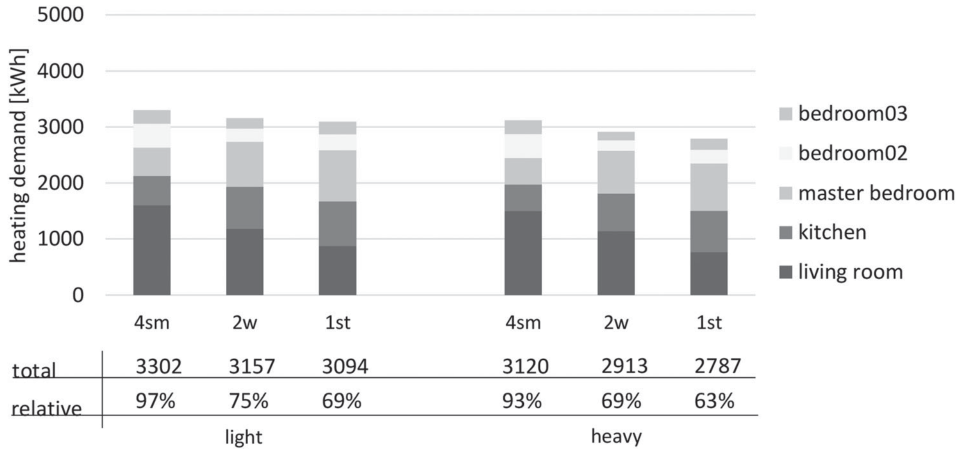


Figure 8. Energy use for heating in the whole house for adaptive heating absolute (kWh) and relative to reference situation (Figure 6) with fixed heating schedule (%).

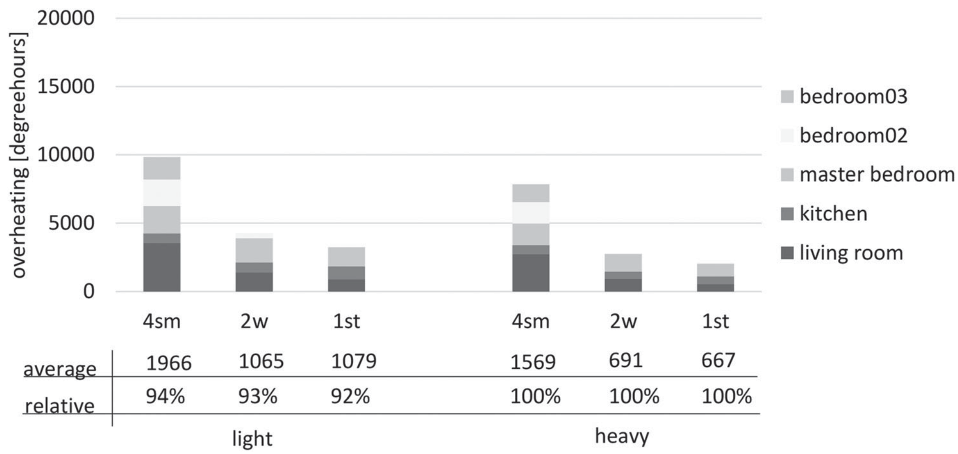


Figure 9. Overheating in degree hours in the whole house for adaptive heating absolute and relative to reference situation (Figure 7) with fixed heating schedule (%).

hours are only calculated for the presence hours. Furthermore, it shows that the overheating is significantly higher for lower thermal mass. The energy saving potential for heating in case of minimized ventilation is slightly lower for higher thermal mass; however, the remaining heating demand is still lower for higher thermal mass.

Adaptive ventilation by operable vents above the windows

To benefit from the energy saving for heating with minimized ventilation without the disadvantage of the overheating problems, the ventilation can be increased whenever there is a surplus of heat in the dwelling. Figure 12 shows the remaining

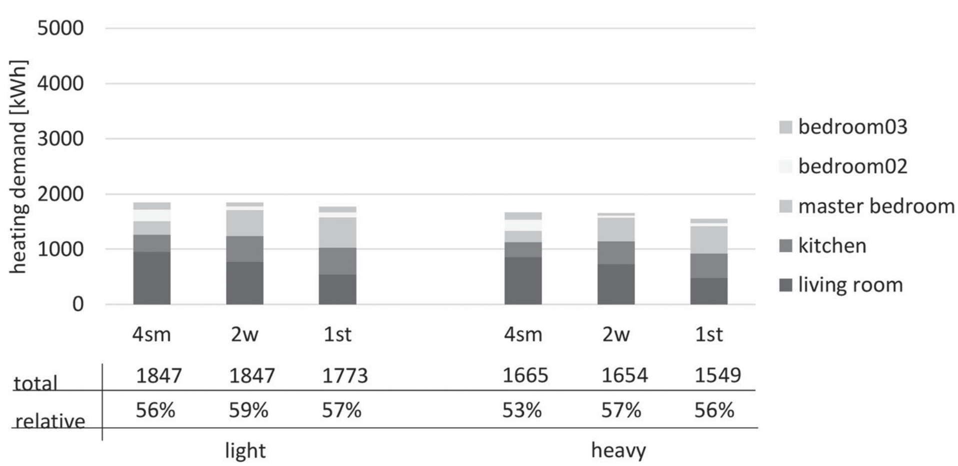


Figure 10. Energy use for heating in the whole house for minimized ventilation absolute (kWh)] and relative to reference situation (Figure 8) with adaptive heating (%).

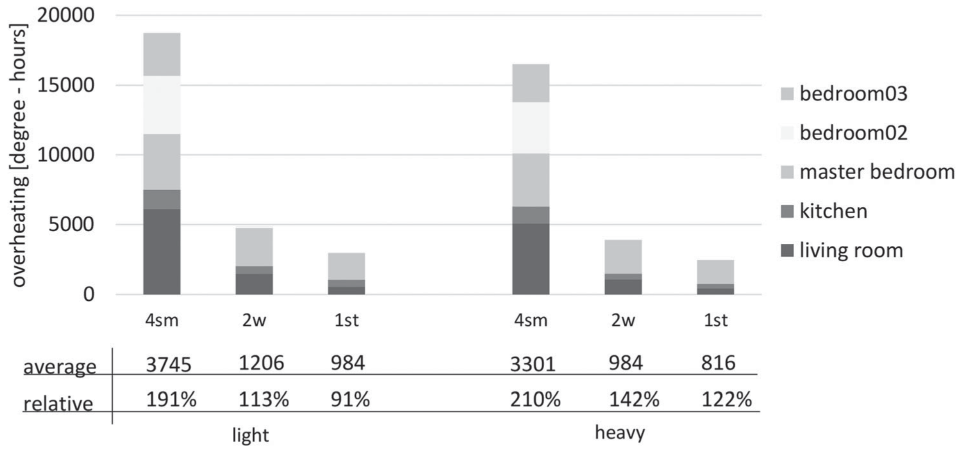


Figure 11. Overheating in the whole house for minimized ventilation absolute (degree hours) and relative to reference situation (Figure 9) with adaptive heating (%).

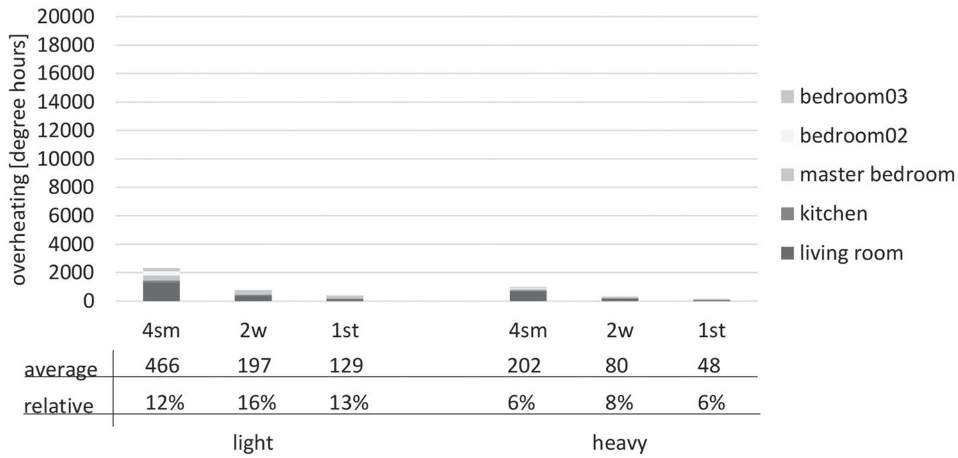


Figure 12. Remaining overheating with adaptive ventilation absolute (degree hours) and relative to minimized ventilation (%) (Figure 11).

overheating in summer by adaptive ventilation absolute (degree hours) and compared to the reference situation of Figure 11 (%). The overheating numbers in the table are the average of overheating degree hours of all used rooms in the occupancy profiles.

As can be seen from Figure 12 compared to Figure 11, the overheating has diminished significantly but it can still be desirable to have an additional cooling system especially for the low thermal mass variant for the family with small children (4sm) with around an average of 466 degree hours left in the living room, kitchen and three bedrooms on the first floor but it will have significantly less energy demand. In a terraced dwelling usually the staircase will be able to provide some stack effect to enhance the extraction of air placing a controllable opening in the top of the staircase. Adding a Venturi-shaped chimney exit will increase the ventilation more. To make it adaptable the openings should be closable (Figure 13).

Adaptive solar gain

The overheating problem caused by the minimum ventilation can be counteracted by blocking solar radiation as well. Figure 14 shows the overheating left in case of adaptive solar gain strategy absolute in degree hours and compared to the reference situation of minimized ventilation (%).

From Figure 14, it can be concluded that the problems that occur in summer due to the minimization of ventilation can be significantly decreased by blocking unwanted solar radiation, more so than with adaptive ventilation. In this situation, not applying cooling will only lead to significant overheating problems in case of a light construction with occupancy by the 4-person household (4sm) with an average of 277 degree hours left in the living room, kitchen and three bedrooms on the first floor. Countering overheating with solar shading is around twice as effective as adaptive ventilation.

Adaptive heating, ventilation and solar gain combined

Applying both adaptive ventilation and solar gain is the most effective way of energy saving for the dwelling because this can result in almost eliminating of the cooling demand with less ventilation rates required so the openings for ventilation can be smaller in theory because most excess heat is already blocked by the shading. In the calculations of this paper, the same vent openings are used but they will be equipped significantly less because most of the excess heat is already blocked by the solar shading. This will result in less frequently used vent openings and lower average ventilation rates.

Figure 15 shows the overheating left in case of adaptive ventilation and solar gain strategy absolute in degree

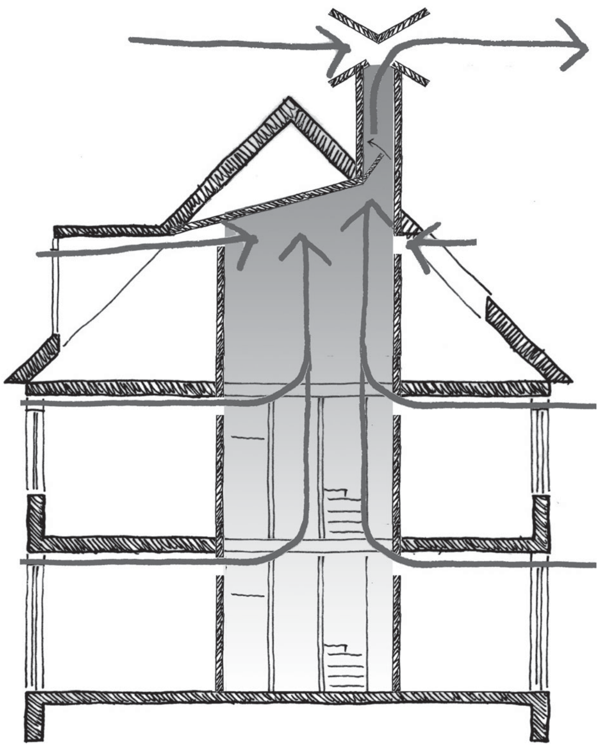


Figure 13. Using the staircase to enhance air flow by extra extraction by the stack effect and the venture-shaped chimney exit.

hours and compared to the reference situation of minimized ventilation (%).

From Figure 15, it can be concluded that as expected the combination of the two measures will almost eliminate virtually all demand for cooling. In case of the light dwelling occupied by the four-person household, 2% of the original overheating is left. With 58 degree hours left on average in the whole house, it is unlikely that active cooling will be required.

Even though the separated measures of dynamic ventilation control and solar shading can prevent most overheating of the home and thus cooling demand, there are clearly benefits in a combination. The vents above the windows could be significantly smaller, which decreases the risk of draught and uses less space in the facade. Furthermore, the smaller the openings the easier it is to make them burglary proof. Additionally, less effective solar shading could be applied as well, which increases the possibilities for materials and techniques and will allow for saving in the cost of the shading. In practice these measures can be optimized together. Furthermore, the need for shading on the North facade can be omitted totally, which can significantly save costs.

Automation versus manual operation

The energy saving potentials of the three strategies in the past sections all assume there is automated control of the settings that choose the right setting for every situation, even when the occupants are not present. This requires advanced domotics with moving mechanical parts to change the position of the window vents and solar shading which can be vulnerable to break down and intentionally inflicted damage and they can be very costly. To be able to make an informed decision about the level of automation chosen in a design, the energy saving potential of all the measures is calculated if applied only during the presence of the occupants as if they could adjust the ventilation and solar shading by hand preferably with an intelligent system of sensors that gives a warning when something should be adjusted.

Figure 16 shows the remaining overheating with adaptive ventilation only when present for all combinations of occupancy profiles and thermal mass in degree hours and relative to the reference situation of minimized ventilation (%).

Figure 17 shows the remaining overheating with adaptive solar shading only when present for all combinations of occupancy profiles and thermal mass in degree hours and relative to the reference situation of minimized ventilation (%).

Figure 18 shows the remaining overheating with adaptive ventilation and solar shading only when present for all combinations of occupancy profiles and thermal mass in degree hours and relative to the reference situation of minimized ventilation (%).

As evidently becomes clear from Figures 16 to 18, the energy saving potential of automation is significant especially for solar shading. In the bedrooms there is no decrease in overheating with presence controlled solar shading because the sun will only shine significantly in the non-occupied hours when the solar

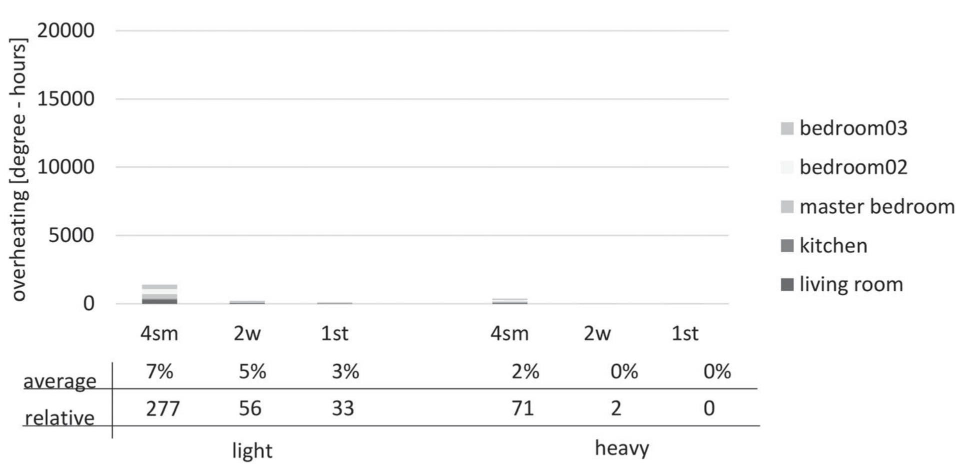


Figure 14. Remaining overheating with adaptive solar gain absolute (degree hours) and relative to minimized ventilation (%) (Figure 11).

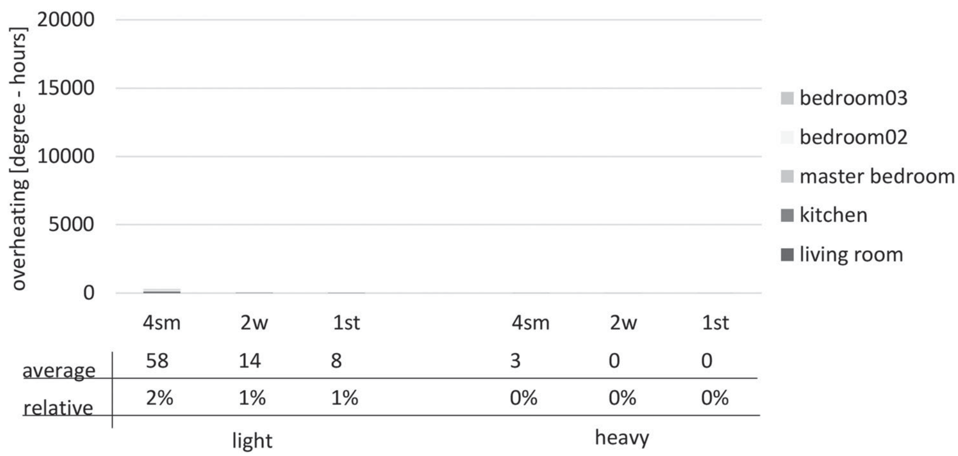


Figure 15. Remaining overheating with adaptive ventilation and solar gain absolute (degree hours) and relative to minimized ventilation (%) (Figure 11).

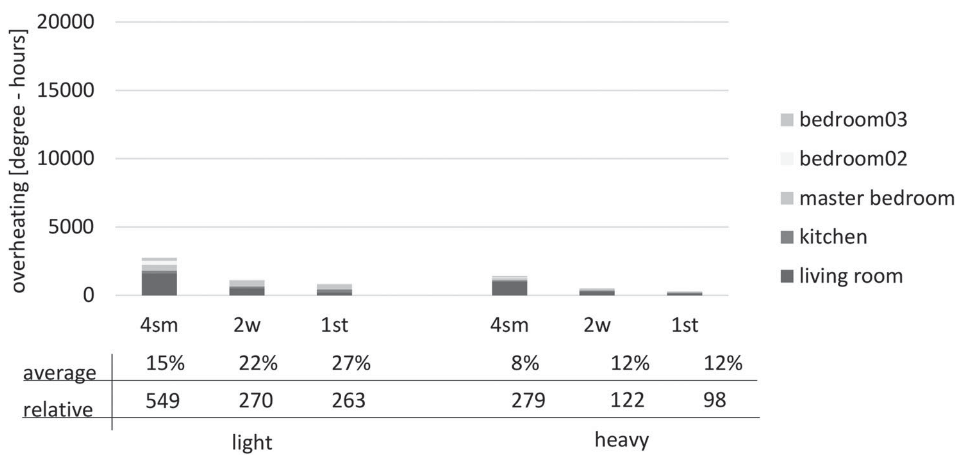


Figure 16. Remaining overheating with adaptive ventilation only when present for all combinations of occupancy profiles and thermal mass absolute (degree hours) and relative to the minimized ventilation variant (%).

shading is not operated. For the adaptive ventilation, the differences are significant but considerably less prominent especially in case of the profile with the highest occupancy rate. The more the people are present, the less the difference between automated and presence operated and the difference is higher with high thermal mass than low thermal mass. Applying solar shading only when the occupants are present will be significantly less effective than automated solar shading, leaving overheating levels almost similar to no solar shading with a decrease in effectiveness of up to 90%. If both measures can be applied only during presence the overheating is still considerable; at most for the family with young children (4sm) there will be an

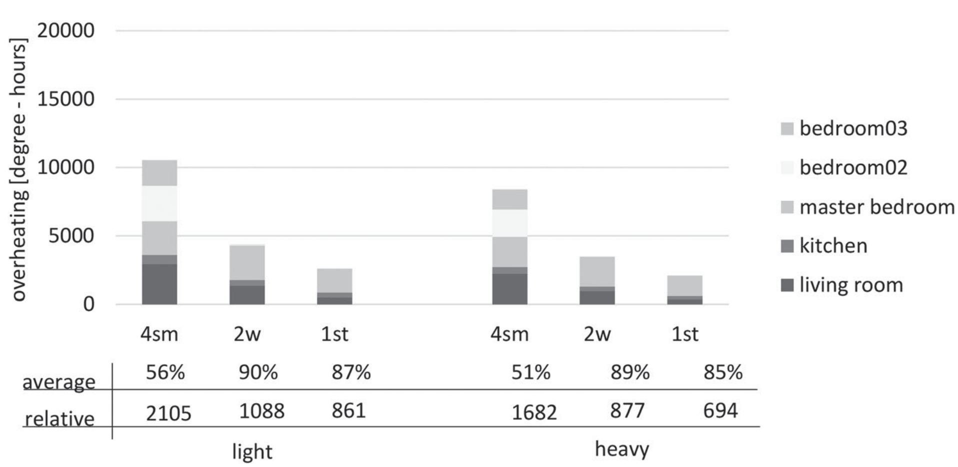


Figure 17. Remaining overheating with adaptive solar shading only when present for all combinations of occupancy profiles and thermal mass absolute (degree hours) and relative to the minimized ventilation variant (%).

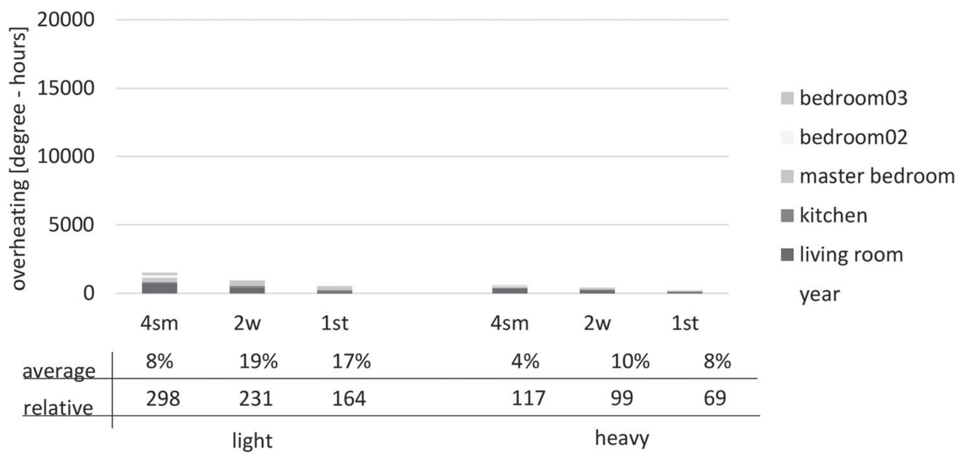


Figure 18. Remaining overheating with adaptive ventilation and solar shading only when present for all combinations of occupancy profiles and thermal mass absolute (degree hours) and relative to the minimized ventilation variant (%).

average of 298 degree hours left in the low thermal mass variant and 117 degree hours in the high thermal mass variant. Nevertheless, this is still a decrease of around 90% compared to the reference situation with minimized ventilation, which is enough to consider omitting the automation, which can be costly and might not be preferred by the users.

Auxiliary energy

Regarding energy saving for (new) techniques, it is important to also incorporate the energy for operation of fans and control systems, the so-called auxiliary energy. In case of the natural ventilation, no extra energy for operation fans is needed, only the fan energy for the mechanical extraction, which is less the less ventilation is applied. Extra auxiliary energy is needed for the operating system and communication as well as the automation of the ventilation openings and solar shading. Communication nowadays is present in most systems, wireless or wired. Most homes will have a network present at which the system can be connected to the Internet to communicate with the components of the systems and also enable the occupant to control the settings at a distance via Internet. It is not expected that the extra electricity for this communication will be anywhere near the energy saving it provides. To make sure no excess energy is spent, the components on the facade can be provided with photovolotaic cells that will provide the little energy needed to operate and they can contribute to the electricity needed to communicate with the system. In this design the solar cells can be applied on the hatch of the window vent. Furthermore, solar cells can be added to the solar screen; however, they would only operate when solar shading is needed. With the further development of the components and the system, these aspects should be taken into account.

Conclusions

Requirements for the Adaptive Thermal Comfort System

This paper described a practical solution for the Adaptive Thermal Comfort System for dwellings as researched in the doctoral thesis *Adaptive thermal comfort opportunities for dwellings; Providing thermal comfort only when and where needed in dwellings in the Netherlands* (Alders 2016). A comparison of these techniques shows that there is not one perfect system or solution and per project all considerations should be made to design an optimal system. It should be noted that there are numerous techniques to construct an Adaptive Thermal Comfort System and the energy saving potential depends on various aspects and the collaboration between the applied techniques in specific scenarios. some of these techniques are already available and some are in various stages of development. In this paper the possibilities of an Adaptive Thermal Comfort System for the near future is researched. Furthermore, the important aspects to consider about the comfort demand and natural thermal energy supply by the weather and how they should be combined are once more stressed to show the approach needed to design the Adaptive Thermal Comfort System. The conditions for the spatial layout of the dwelling to enable effectiveness of the adaptive measures is described as well as the aspects needed to be considered for control of the systems.

Preconditions for the effectiveness of an Adaptive Thermal Comfort System

Orientation

To optimize effectiveness of the adaptive solar gain both for saving energy for heating as well as cooling by allowing maximum solar radiation in and blocking maximum solar radiation, the rooms with the highest heating demand and/or very variable comfort demand should be oriented in the direction where most solar radiation comes from, considering the time of day of the highest heating demand.

Ventilation

To ensure the effectiveness of the adaptive ventilation the layout should not hinder the air flow through the building. In case of a heating demand this free air flow can be temporarily disabled by (automatically) closing doors and vents. From the calculations it becomes clear that the concept (Figure 5) with large operable vents above the windows of 30 cm together with operable vents above the internal doors and an additional opening in the roof in the stair case has significant reduction of overheating. To be able to reduce the overheating more by ventilation, this paper suggests a concept to enhance the ventilation more by stack ventilation and a Venturi-shaped chimney (Figure 13). These will have an additional advantage of lowering the need for fan energy for the mechanical exhaust.

Automation

An optimal Adaptive Thermal Comfort System is automated and therefore the system should be provided with sufficient information about the weather and occupant at the right time. For this a design should be made for the sensors and information transfer to the control unit.

This automation also implies communication between the control unit and the end units, which should be able to operate automatically by a signal without interaction with the user. In this design, it is crucial to consider the acceptance of the user of this fully automated system.

Composition of the adaptive components of an Adaptive Thermal Comfort System in a standard reference dwelling in the near future

Adaptive heating: heating only where and when needed at the level needed by the user.

Automated solar shading: solar shading controlled to block solar radiation when needed to prevent overheating and allowing maximum amount of solar radiation in the heating season to decrease the heating demand.

Automated adaptive ventilation: ventilation (preferably by natural ventilation to save fan energy and space for ducts) controlled to discard excessive heat when needed to prevent overheating and minimize ventilation for fresh air in the heating season to decrease the heating demand.

Figure 19 shows a visualization of a full concept of applying an Adaptive Thermal Comfort System into a standard reference dwelling with techniques nowadays available.

Conclusions: energy saving potential of the Adaptive Thermal Comfort System in a standard reference dwelling

In this paper, the conclusions made by the preliminary calculations in the thesis are verified with concepts developed as examples for an Adaptive Thermal Comfort System to be applicable in a current design. It shows that minimizing the ventilation in winter can save almost half of the energy used for heating and that by adaptively blocking the solar radiation and raising the

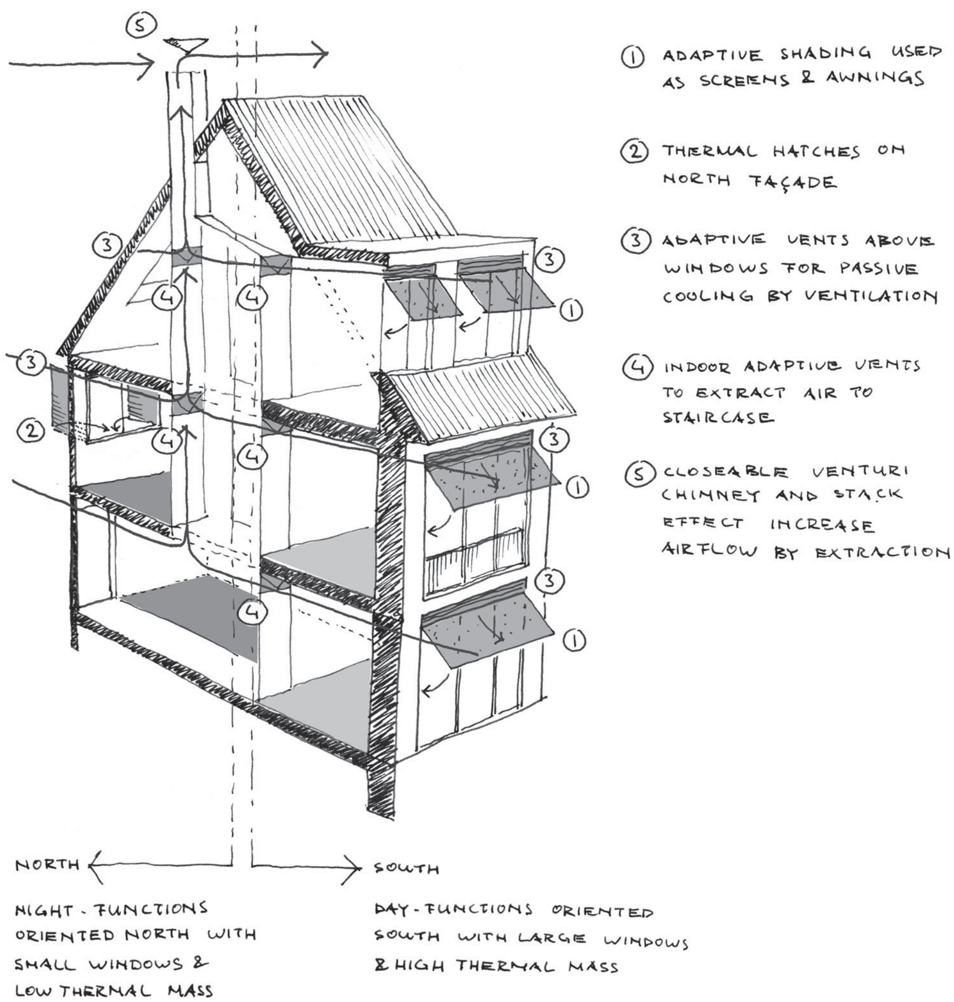


Figure 19. Elements of an Adaptive Thermal Comfort System in a standard Dutch dwelling.

Table 8. Summary of energy saving potential of the Adaptive Thermal Comfort System based on the generic calculations.

		4sm		2w		1st		
		Light	Heavy	Light	Heavy	Light	Heavy	Average
Adaptive heating	Energy saving potential[a]							
	Heating	3%	7%	25%	31%	31%	37%	22%
	Overheating	–	–	–	–	–	–	–
Minimized ventilation	ACPH (1/h)	0.5 + 0.2*p						
	Energy saving potential[a]							
	Heating	44%	47%	41%	43%	43%	44%	44%
	Overheating[b]	–	–	–	–	–	–	–
Adaptive heat loss coefficient	ACPH (1/h)	0.5–10						
	Energy saving potential[a]							
	Heating	–	–	–	–	–	–	–
	Overheating	88%	94%	84%	92%	87%	94%	90%
	Automation[c]	−2%	−2%	−6%	−4%	−14%	−6%	−6%
Adaptive solar factor	Fc	$0–G_w * f_g$						
	Energy saving potential[a]							
	Heating	–	–	–	–	–	–	–
	Overheating	93%	98%	95%	100%	97%	100%	97%
	Automation[c]	−49%	−49%	−86%	−89%	−84%	−85%	−74%
ATCS	Energy saving potential[a,d]							
	Heating	59%	61%	66%	68%	68%	71%	65%
	Overheating	98%	100%	99%	100%	99%	100%	99%
	Automation[c]	−6%	−3%	−18%	−10%	−16%	−8%	−10%

[a]These values are based on the calculations with the assumptions in the thesis (Alders 2016) and are based on the reference dwelling of AgentschapNL. The variation in energy saving potential per situation depends on the thermal mass level.
[b]Overheating escalates without additional measures in summer.
[c]In this row, the negative percentage represents the decrease in effectiveness against overheating if the adaptive measure is not automated.
[d]The total energy saving potential of all discussed measures compared to the reference situation with average insulation, average solar factor and constant ventilation (1.25 1/h).
–, Not applicable.

ventilation can prevent overheating that can occur for an important part as a result of this minimized ventilation. This shows that with techniques already available, a dwelling can be highly reactive to the changes in the weather, optimizing the thermal heat balance for the majority of occurring situations. It also shows that the measures to vary the ventilation and the solar factor are well within the range of possibilities already available with common techniques. The ventilation openings above the window of approximately 30 cm can create a high enough ventilation rate together with openings above the internal doors of also 30 cm to prevent the dwelling from overheating. The ACPH can rise up to 12 1/h; however, this is a peak value that only occurs less than 5% during the summer months. The prevention of overheating can be enhanced by additional measures to propagate natural air flow for ventilation as well as minimizing the needed for fan energy for mechanical extraction.

The need for cooling can be effectively diminished using the proposed flexible measures. Practically, this means that there should be no need for installing active cooling in the dwelling and thus an energy saving potential of 100% can be reached. For saving energy on heating the situation of minimized ventilation with heat recovery is clearly the best option. The total energy saving compared to fixed natural ventilation is dramatic (almost 50% energy saving). However, as seen before applying all measures for energy conservation in the heating season needs counteractions in the cooling season to prevent overheating. Table 8 shows a summary of the characteristics and energy saving potential for all separate measures and in the end of all measures together. In all cases the remaining heating demand is less than half of the original demand ranging from 41% to 29%. The loss in effectiveness of the adaptive solar gain is markedly decreased without automation with an average of 75% less energy saving, whose effect is most apparent with lower occupancy rate. The energy saving potential for the combined measures without automation drops with 30% on average, making the automation crucial for the Adaptive Thermal Comfort System.

Smart application of operable windows and solar shading will eliminate the need active cooling in the Dutch residential sector while applying high energy saving for heating demand as the Adaptive Thermal Comfort System shows.

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Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Noortje Alders has acquired her PhD at the Delft University of Technology (the Netherlands) with her thesis titled "Adaptive thermal comfort opportunities for dwellings; Providing thermal comfort only when and where needed in dwellings in the Netherlands" which researches passive measures for energy saving for heating and cooling in Dutch dwellings by automated ventilation and solar shading. Currently she runs her own company for education, design and consultancy for energy and building physics. Prior to her PhD candidacy she has worked as an architect and building consultant at various companies.

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