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The effect of dynamic solar shading on energy, daylighting and thermal comfort in a nearly zero-energy loft room in Rome and Copenhagen

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Abstract

Dynamic solar shading is commonly suggested as a means of reducing the problem of overheating in well-insulated residential buildings, while at the same time letting daylight and solar irradiation in when needed. To critically investigate what dynamic shading can and cannot do compared to permanent alternatives in buildings with very low space-heating demand, this study mapped and compared energy, daylighting and thermal comfort for various combinations of window size and glazing properties, with and without dynamic shading. The study considered a loft room with sloped roof windows and moderate venting options in nearly zero-energy homes in Rome and Copenhagen. The more flexible solution space with dynamic shading made it possible to either reduce the time with operative temperatures exceeding the comfort limit by 40-50 h or increase daylighting by 750-1000 h more than could be achieved without shading. However, dynamic shading could not improve the optimum space-heating demand of the loft room in any predictable way, and without using dynamic shading, illuminances of 300 lx in 75% of the space could be achieved in 50-63% of the daylight hours with no more than 40-100 h exceeding the comfort ranges as defined by the Adaptive Thermal Comfort (ATC) model.

Keywords: Dynamic solar shading, Solar-control coating, Roof windows, Window design, Residential buildings, Space heating, Climate-based daylighting, Adaptive thermal comfort

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Highlights

- *Dynamic and permanent shading strategies were studied for roof windows.*
- *Energy, daylighting and thermal comfort potentials were identified and compared.*
- *Dynamic shading had almost no potential for improving optimum space heating.*
- *Up to glazing-to-floor ratios of 10-15% dynamic shading could mainly improve comfort.*
- *For large solar control coated glazing, dynamic shading gave 750-1000 h more daylighting.*

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1. Introduction

As a result of ambitious energy strategies in the European Union, all new buildings are required to consume nearly zero energy by the end of 2020 [1]. This creates a strong need for research in cost-efficient window solutions and technologies that support very low energy consumption for space heating without compromising on daylighting and thermal comfort.

Several studies have identified overheating in the summer period and in the transitional seasons between winter and summer as a major problem in very well-insulated residential buildings in Europe, even in colder climates [2-5]. Dynamic solar shading is a commonly suggested means of reducing such problems of overheating, while still preserving a high access to daylight and solar irradiation through windows when needed [6-12]. In a house called 'Home for life' [6], which was designed and constructed in Denmark in accordance with the Active House specifications [13], dynamic shading combined with efficient venting strategies made it possible to achieve an average daylight factor of 5% without overheating, with overheating evaluated on the basis of the Adaptive Thermal Comfort (ATC) model [14]. Similarly, a systematic parameter study by Petersen [7] on window size, user patterns and cooling strategies in future homes based on the same daylight target doubts that it is even possible to achieve adequate daylighting in very low-energy buildings unless solar shading is applied to reduce overheating and thermal comfort is evaluated in accordance with the ATC model. Other studies on very well-insulated houses and nearly zero-energy homes, however, have questioned the importance of dynamic solar shading in buildings with a very low space-heating demand, due to the reduced need for solar gains in these buildings [2, 15-18]. They suggest that solar control coated glazing with lower solar energy transmittances (g-values) and high selectivity for daylighting could be used to prevent overheating in such buildings, without critically affecting the space-heating demand. Such permanent glazing solutions are cheaper in comparison with dynamic shading and they do not face the same operational challenges or depend on successful control to perform well. On the other hand, dynamic shading options may be highly valued by users and designers who appreciate architectural freedom and user-flexibility in controlling the indoor environment. Currently, however, informed decisions on one or the other shading strategy tend to suffer from the lack of sufficient information about what can actually be achieved with each of the shading strategies on energy, daylighting and thermal comfort all at once.

1.1. Aim of study

The aim of this study was to provide an example of what dynamic solar shading can and cannot do compared to solar control coated glazing in very well-insulated homes. Only effects of the shading strategies on transmittances of light and solar energy were considered. Potential effects on thermal transmittances [19-20] were not considered. The direct effects of dynamic solar shading would then typically be improved thermal comfort, slightly less daylighting and preferably no changes in space-heating demand at all. These effects can be determined in a relatively straight forward way by comparing the same window option with and without shading. In contrast, the full potential on energy, daylighting and thermal comfort of choosing one or the other shading strategy has to be derived from the flexibility found with each of the shading strategies before it can be compared. To be able to compare the full potential of the two shading strategies, we therefore first mapped the performance of various combinations of window size and glazing properties on energy, daylighting and thermal comfort, with and without the use of a supplementary dynamic shading device. Then, the best potential achievements on energy, daylighting and thermal comfort for the options with acceptable daylighting and thermal comfort were identified and compared.

This was done for a loft room with 45-degree-sloped roof windows, located in nearly zero-energy homes in Rome (Italy) and Copenhagen (Denmark). Loft rooms represent a situation with large risk of overheating and larger heat losses than in the rest of the building. On the other hand, sloped roof windows are known to provide twice as much daylighting as faade windows do [21].

To achieve a realistic picture of the energy, daylighting and thermal comfort potentials of the two shading strategies, the effect of the shading strategies on daylighting has to be taken into account in the analysis. Since this is only possible if daylighting is modelled dynamically throughout the year, the use of a climate-based approach for evaluation of daylighting (see Section 2.3.3) was central for carrying out this study, even though this is not yet common practice for housing.

1.2. Literature review

For office buildings, several studies have examined the thermal performance of dynamic solar shading along with effects on daylighting or electricity use for artificial lighting [22-40]. For residential buildings, studies by Mavrogianni et. al [8], Apte, Arasteh & Huang [9], Gugliermetti & Bisegna [10], Vanhoutteghem & Svendsen [15], Arasteh et. al [41], Firląg et. al [42], O'Brian, Athienitis & Kesik [43], Tsikaloudaki et. al [44], Kim et. al [45], Ali Ahmed [46], Karlsson, Karlsson & Roos [47] and Sullivan et. al [48] focused mainly on the thermal performance of solar shading. Considering the topic of dynamic roof windows, Klems [49] examined the summer performance of an electrochromic skylight through measurements in a test chamber, and amongst others concluded that better means of evaluating the benefits of daylighting would be needed to quantify realistically the performance of dynamic skylights compared to fixed-property skylights. Finally, not specifically focusing on roof windows, studies by Foldbjerg & Asmussen [6], Petersen [7], Du [50], Du, Hellström & Dubois [51], Yao & Zhu [52], DeForest et. al [53] and Carlucci et. al [54] considered both the thermal performance of solar shading and the effect of the shading on daylighting, visual comfort or electricity use for lighting in residential buildings. Since these studies assumed either fixed size or fixed properties of the glazing options compared, however, the full potential of using solar-control coating or dynamic shading was not transparently addressed. By exploring these potentials, the present study contributes to new knowledge within the field.

2. Methodology

2.1. Loft room in a nearly zero-energy residential building

The study considered a loft room with floor dimensions of 4 x 4 m and ventilated room volume of 40 m^3, located in the middle part of the 1st floor of a 1½-storey single-family house (Figure 1). This location represents the largest risk of overheating at the 1st floor. The loft room had single-sided daylighting access and natural venting options through two 45-degree-sloped roof windows in the south-facing roof surface. These were reasonable distributed on the width and positioned close to the top edge of the roof surface for optimal diffuse daylight access (see Figure 1). The loft room was modelled as a separate zone with no air or heat exchange with other rooms in the building. No external obstructions were taken into account, and the surface reflectance was 70% for walls and ceilings and 30% for floors. The insulation of the roof and the settings for venting, infiltration and heat-recovery (Table 1) were selected to reflect the room's location in a single-family house that based on findings from previous studies [16-18] and test-simulations of different zones in the house was known to consume nearly zero-energy (as defined in Section 2.3.1). In general, the model assumed air-tight construction details of very high quality and mechanical ventilation with ambitious heat recovery efficiency to ensure acceptable fresh-air supply all year round with minimum heat losses. The use of the room is dwelling, as defined according to standard practice for documenting thermal comfort and energy consumption of residential buildings in Denmark [55]. This practice assumes a constant heat load per floor area from people and equipment in all rooms (Table 1), corresponding to an average size family with simplified user patterns living in an average size house.

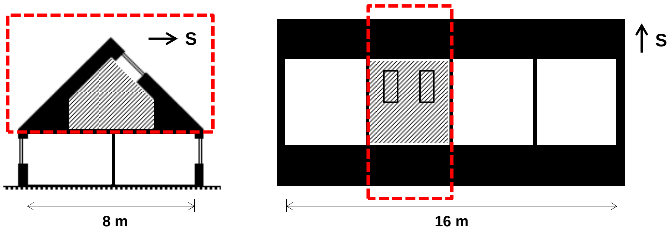


Figure 1: Sketch indicating the location of the loft room in the middle part of a 1½-storey single-family house with simplistic floor plan: Vertical section of the house to the left and horizontal section of the 1st floor to the right.

2.2. Location and climate

The loft room was modelled for the two locations of Rome (latitude 41.80) [56] and Copenhagen (latitude 55.40) [57]. The investigation was carried out from a Danish perspective. The loft room considered is therefore more typical for Northern latitudes than for Mediterranean ones, and is not intended to represent common housing in Rome. However, to see how the results would be affected by two significantly different European climates, the location of Rome was included to represent an arbitrary climate in the Mediterranean region.

Table 1: Building specifications for the thermal simulation model.

	Rome	Copenhagen
Roof construction		
U-value[1)] (W/m^2 K)	0.15	0.08
Total thickness (mm)	300	550
Insulation thickness (mm)	150	400
Effective surface area exposed to the outside (m^2)	44.40	48.40
System properties and internal loads		
Heating set-point (°C)	20	20
Venting set-point (°C)	23	23
Infiltration rate (h^{-1})	0.05	0.05
Maximum rate for natural venting (h^{-1})	4	3
Mechanical ventilation rate (h^{-1})	0.6	0.6
Efficiency of heat recovery (-)	0.9	0.9
Loads from people, equipment and lighting (W/m^2)	5	5

1) Includes linear heat losses.

2.3. Performance parameters and evaluation criteria

Assuming that thermal comfort could be achieved by efficient natural venting and appropriate window solutions, no mechanical cooling was installed. Furthermore, energy use for artificial lighting is not part of Danish energy requirements for dwellings. Energy use was therefore evaluated on the basis of space-heating demand alone (Section 2.3.1), while daylighting and thermal comfort were evaluated as separate performance parameters (Section 2.3.2 and 2.3.3).

2.3.1. Evaluation of space-heating demand

In Denmark, the annual primary energy usage for nearly zero-energy residential buildings is defined as no more than 20 kWh/m^2 [58]. This must cover space heating, domestic hot water, and electricity for pumps and ventilation. Based on test simulations of different zones in the house it was found that the space-heating demand (or end energy usage for heating) of the loft room should be no more than approximately 16 kWh/m^2 per year, for the building in total to consume nearly zero energy in accordance with Danish regulations. The insulation level and the target of 16 kWh/m^2 per year for space heating could be more or less in Rome, depending on primary energy sources, the result of cost-benefit analyses, and whether houses need to be insulated more so as to allow for cooling in the overall energy budget. However, no specific requirements for nearly zero-energy have been defined yet, so for Rome, the insulation level chosen to comply with Danish practice is just a suggestion.

2.3.2. Evaluation of thermal comfort

Assuming that the occupants were free to use windows for venting, to adjust their clothing, and in other ways adapt to indoor conditions, we used the Adaptive Thermal Comfort (ATC) model in EN 15251 [14] to evaluate thermal comfort. The ATC model states that the comfortable operative temperature is a function of the running mean outdoor air temperature at the location. With this model, the upper limit for thermal comfort is not a fixed temperature, but a variable temperature that depends on recent temperatures outdoors. With view to standard practice procedures in Denmark for documenting thermal comfort in dwellings [55], the criterion for overheating was set to maximum 100 hours (h) per year with operative temperatures exceeding the upper comfort limit provided by Class II of this model. In Denmark, 100 h above the adaptive comfort limit equals approximately 100 h above 27°C [7]. In Rome, analyses of the simulation output for operative temperatures in the present study showed that 100 h above the adaptive comfort limit equalled approximately 500 h above 28°C, 800 h above 27°C and 1,300 h above 26°C for the loft room considered.

2.3.3. Evaluation of daylighting

The establishment of reasonable daylight criteria is an issue under continuous debate, supported by ongoing research on the effects of daylighting on human health [59-61], and for homes sufficient daylighting is only vaguely defined yet. With view to the recommendations established by IES [62] for Spatial Daylight Autonomies in offices, we assumed that daylighting was acceptable if 75% of a horizontal plane 0.85 m above floor level received 300 lx for at least 50% of the daylight hours. For the south-oriented loft room considered, this criterion corresponded to a median daylight factor in the space of approximately 3% for the location in Copenhagen and slightly above 1.5% for the location in Rome. These values both correspond well with the climate-dependent daylight factors suggested by Mardaljevic and Christoffersen [59-60], which means that also a minimum access to diffuse daylighting of 300 lx for 50% of the daylight hours will be likely in half of the space area.

Throughout this paper, daylighting above the suggested criterion will be quantified in terms of time, so an improvement in daylight autonomy (DA) of 1% means there will be approximately 44 hours more every year where the illuminance threshold of 300 lx is met in at least 75% of the space.

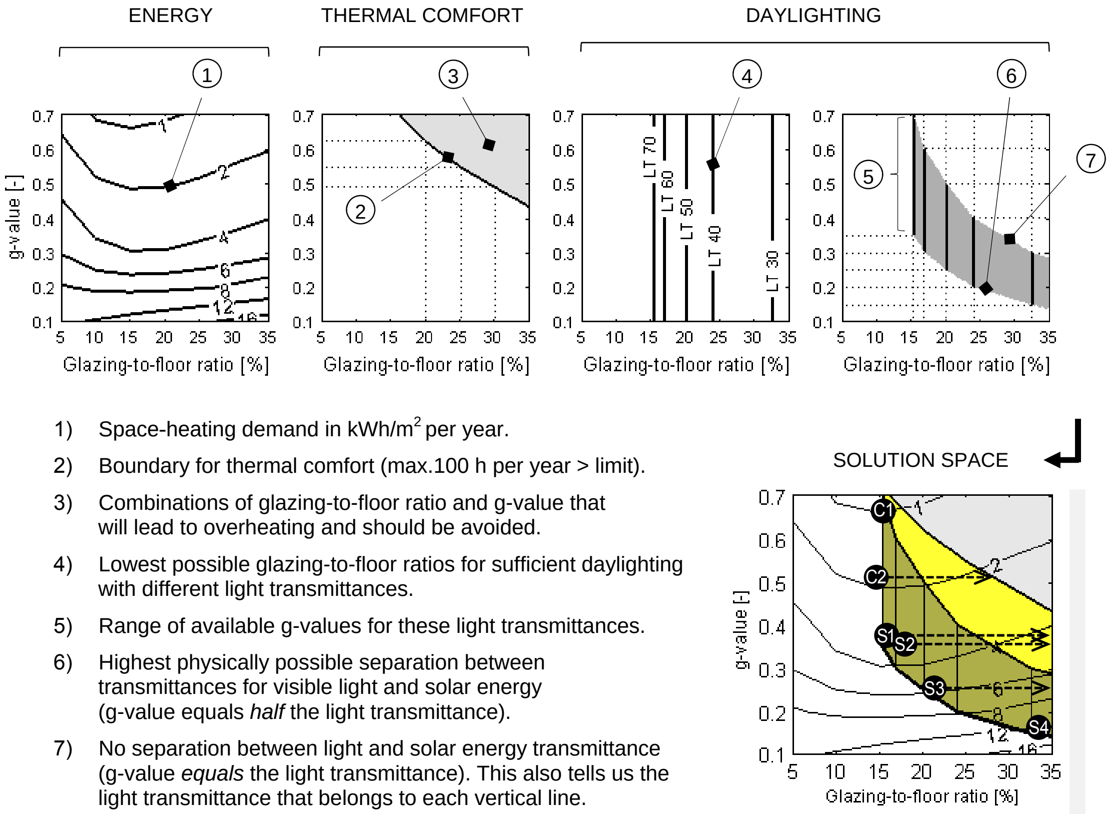
2.4. Identifying the potential achievements

To be able to identify the potential achievements on energy, daylighting and thermal comfort with and without dynamic shading, we carried out a parametric study for each case, and used the glazing diagram [17-18] (explained in Figure 2) to systematise and illustrate the results.

Table 2: Thermal properties of glazing and frame for the windows investigated.

		Glazing U-value (W/m^2 K)	Frame properties				
			Width (m)	U-value (W/m^2 K)	Psi g (W/m K)	Psi w (W/m K)	Specific heat loss[1)] (W/K)
Rome	STANDARD	1.3	0.09	1.5	0.050	0.10	1.460
Copenhagen	STANDARD	0.7	0.09	1.5	0.050	0.10	1.460
	IMPROVED	0.5	0.11	0.7	0.025	0.05	0.768

1) Specific heat loss of the frame, including heat losses through the connection between frame and glazing and the connection between frame and roof, calculated based on a reference window with outer dimensions 1.23 by 1.48 m.



1) Space-heating demand in kWh/m^2 per year.

2) Boundary for thermal comfort (max.100 h per year > limit).

3) Combinations of glazing-to-floor ratio and g-value that will lead to overheating and should be avoided.

4) Lowest possible glazing-to-floor ratios for sufficient daylighting with different light transmittances.

5) Range of available g-values for these light transmittances.

6) Highest physically possible separation between transmittances for visible light and solar energy (g-value equals *half* the light transmittance).

7) No separation between light and solar energy transmittance (g-value *equals* the light transmittance). This also tells us the light transmittance that belongs to each vertical line.

Solution space (in yellow):
Some existing clear glazing products (C1-C2) and solar control coated glazing products (S1-S4) with different properties (U-value/LT/g-value) are shown in the solution space for daylighting and thermal comfort to exemplify its use:
C1-1.1/69/0.67, C2-0.5/72/0.51, S1-1.0/65/0.39, S2-0.5/57/0.36, S3-1.0/46/0.26, S4-1.0/28/0.17.
The arrows indicate how glazing-to-floor ratio can be increased up to the thermal comfort limit.

Figure 2: Reader's guide to the glazing diagram.

For Copenhagen, both a roof window with the best thermal properties of glazing and frame commonly available on the market today (referred to as 'standard') and a very well-insulated state-of-the-art product that is not yet commonly available (referred to as 'improved') were studied (Table 2). For Rome, a window with a standard frame, but slightly higher thermal transmittance (U-value) of the glazing was studied (Table 2) [16]. For each of these three sets of thermal properties, hourly space-heating demand and operative temperatures were determined with and without dynamic shading for each combination of glazing-to-floor ratio and g-value given in Table 3. For this, the building simulation tool EnergyPlus [56] was used in combination with the tool jEPlus [63-64] for automated parametric analysis. Furthermore, hourly indoor illuminance distributions were determined for each combination of glazing-to-floor ratio and light transmittance (LT) given in Table 3, using the RADIANCE-based daylighting analysis tool DAYSIM [65] and a sensor point grid with a mask width of 0.2 m positioned 0.85 m above floor plane.

Table 3: Variables used in the parametric analysis carried out with and without dynamic shading.

Parameter	Rome	Copenhagen
Thermal properties	STANDARD	STANDARD IMPROVED
Glazing-to-floor ratio[1)] (%)	5 10 15 20 25 30 35	5 10 15 20 25 30 35
Glazing g-value (-)	0.1 0.2 0.3 0.4 0.5 0.6 0.7	0.1 0.2 0.3 0.4 0.5 0.6 0.7
Light transmittance (%)	10[2)] 20[2)] 30 40 50 60 70	10[2)] 20[2)] 30 40 50 60 70

1) Daylighting was modelled for the ratios 2.5-40% in increments of 2.5%, and for simplicity, roof thicknesses in both climates were assumed to be 0.45 m. The ratios refer to internal floor area.

2) Also modelled as diffuse transmittance in the simulations used to find illuminances with shading.

The simulation outputs were then handled and structured in the following way (explained with basis in the reader's guide to the glazing diagram given in Figure 2):

- Energy: The annual space-heating demand expressed in kWh per m^2 floor area (16 m^2) was plotted as a function of g-value and glazing-to-floor ratio (1).
- Thermal comfort: The annual hours with operative temperatures exceeding the comfort limit (see Section 2.3.2) were summarised. The maximum g-value without overheating (no more than 100 hours above the limit) was then extracted for each glazing-to-floor ratio, using linear interpolation, and plotted as the boundary for thermal comfort (2-3).
- Daylighting: The percentage of daylight hours with at least 300 lx in 75% of the space was found for every combination of light transmittance and glazing-to-floor ratio. The minimum glazing-to-floor ratio needed to meet the targeted daylight autonomy of 50% (see Section 2.3.3) was then extracted for each light transmittance using linear interpolation, and illustrated as the vertical lines in the glazing diagram (4). Knowing that the g-value of glazing with optimal solar-control coating cannot be lower than approximately half of the light transmittance, a boundary for daylighting can be drawn, indicating the options with minimum glazing size and g-value for sufficient daylighting (6).
- Solution space: The daylight boundary (6), together with the boundary indicating overheating (2), then forms a solution space defining the options with acceptable daylighting and thermal comfort.

The way this solution space was finally used to quantify and compare energy, daylighting and thermal comfort potentials with and without shading for options at the boundaries, will be explained in connection with the results (Section 3.1-3.2). For more examples of its use is referred to the papers by Vanhoutteghem et. al [17] and Skarning, Hviid & Svendsen [18].

Table 4: Minimum glazing-to-floor ratio for daylighting with LT 70% for various shading factors with the set-point of 300 W/m^2 for irradiation and 18°C for outdoor temperatures.

Shading factor	Rome	Copenhagen
1.00 (no shading)	6.6	9.7
0.30	7.7	9.8
0.15	9.8	10.8
0.10	11.4	11.6
0.05	13.8	12.4

2.5. Dynamic shading device and control strategy

The dynamic solar shading device modelled corresponds to an external roller shade with shading factor 0.15, covering the whole glazed part of the windows when activated. In daylight calculations, it was assumed that the combination of glazing and shade had a perfectly diffuse transmittance corresponding to the shading factor times the light transmittance of the glazing (Table 3). This diffuse modelling of the glazing with shading gives slightly better daylight conditions than would have been the case if modelling the same transmittance as specular. The illuminance distributions with shading were extracted from diffuse simulations of the two transmittances 10% and 20%, using linear interpolation.

The shading was activated when both the set-point of 18°C for outdoor air temperatures and the set-point of 300 W/m^2 for total diffuse and direct solar irradiation on the window, were exceeded. With these control settings, the shading will be activated for about 15% of the daylight hours in Copenhagen and for about 35% of the daylight hours in Rome.

It should be noted that this shading strategy was selected with view to a low space-heating demand, and to daylighting as the main motivation for increasing the window size. The choice was therefore a solution that improved thermal comfort significantly, while affecting space-heating demand and minimum window sizes for daylighting as little as possible.

The shading strategy was found through an iterative process, where the effect of various combinations of shading factor and set-points on energy, daylighting and thermal comfort were investigated. Amongst other things, this process revealed that lowering the irradiation set-point to less than 300 W/m^2 did not improve thermal comfort significantly. The temperature set-point of 18°C, which complies well with the findings by Firląg et. al [42], was chosen to avoid increasing the space-heating demand. Moreover, Table 4 shows for the chosen settings how various shading factors affected the minimum glazing-to-floor ratios for daylighting when the light transmittance was 70%.

3. Results and discussion

3.1. The solution spaces with and without dynamic shading

Figure 3 shows the glazing diagrams with and without dynamic shading for Rome and Copenhagen. Considering the direct effect of dynamic shading, it may be seen that the contour lines for space heating are the same with and without shading. This is because the shading did not affect space-heating demand with the set-point of 18°C for outdoor temperatures (Section 2.5). Furthermore, minimum glazing sizes for daylighting increased only slightly in Copenhagen, while they increased more visibly in Rome. When looking at the thermal comfort, however, the use of dynamic shading reduced overheating to a level where considerably higher g-values could be used in combination with the various glazing-to-floor ratios without overheating. The acceptable options for daylighting and thermal comfort (marked in yellow), were therefore more with dynamic shading than without.

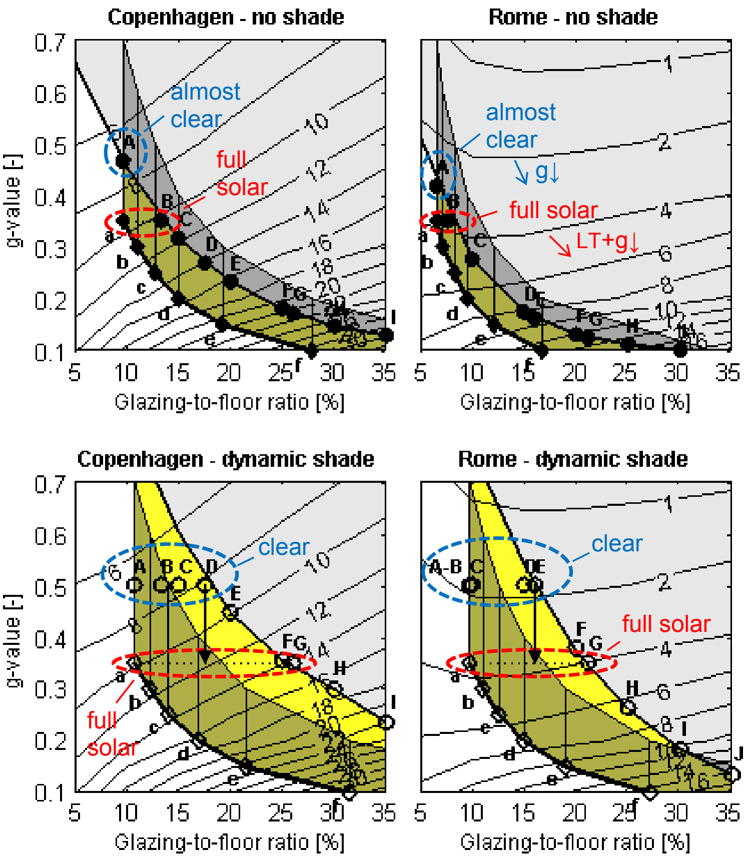


Figure 3: Comparison of solution spaces with no additional shading device (top) and using an external dynamic shading device (bottom). Illustrated for roof windows with standard thermal properties (see Table 2) in Copenhagen (left) and Rome (right). The evaluation points A-J and a-f are used for comparison of potential energy, daylighting and thermal comfort achievements with and without dynamic shading.

With lower shading factors and set-points, the comfort limit could have been moved towards even higher g-values and glazing-to-floor ratios, but this would also require significantly larger window sizes for daylighting (see Section 2.5). Such shading options were therefore considered less economically favourable and would not necessarily have led to more flexibility.

3.2. Potential achievements with and without dynamic shading

To be able to discuss what the differences in solution space mean for potential achievements on energy, daylighting and thermal comfort, a number of evaluation points were introduced, representing options on the limits of what is physically possible or acceptable for daylighting and thermal comfort (see points A, B, C. etc. and a, b, c, etc. in Figure 3):

- The points A-J represent options on the limits of what is either physically possible or acceptable for thermal comfort. This scenario holds the options with the lowest space heating demand and the best daylighting.
- The points a-f represent options that are just acceptable for daylighting with LT 20-70% and optimal solar-control coating. This scenario holds the options with the best thermal comfort.

Figure 4-5 shows the achievements on energy, daylighting and thermal comfort for these evaluation points with and without dynamic shading. To indicate how the shading affected winter comfort, the comfort plot (bottom row) also shows the number of hours above 26°C in winter for the cases where this occurred. Maximum transmittances of LT 70% and g-value 0.5 were assumed for the low-energy glazing considered (see the options referred to as 'clear' in Figure 3, bottom row). Moreover, LT, g-value and glazing-to-floor ratio of each evaluation point can be found in the bottom of Figure 4-5.

3.2.1. Limited potential for improving the optimum space heating

Without dynamic shading the lowest space-heating demand in both climates was achieved with the options that just met the daylighting and thermal comfort criteria with the highest possible g-value. These are the options with LT 70% and g-values of 0.48 in Copenhagen and 0.42 in Rome, referred to as 'almost clear' in Figure 3 (see point A, top row).

The use of dynamic shading made it possible to either increase the g-value by approximately 0.3 or use approximately 10% larger glazing-to-floor ratios than without shading (see Figure 3). These are both changes that could potentially reduce the space-heating demand. Due to the maximum g-value of clear low-energy glazing (assumed to be 0.5), however, only slightly higher g-values could be used with dynamic shading than without (see the options referred to as 'clear' in Figure 3, bottom row). Comparison of the space-heating demand with and without dynamic shading for point A in Figure 4-5 (top-left), therefore shows that the use of dynamic shading had the potential of reducing space-heating demand by only 0.3 kWh/m^2 in Copenhagen and 1.1 kWh/m^2 in Rome. This outcome may also be

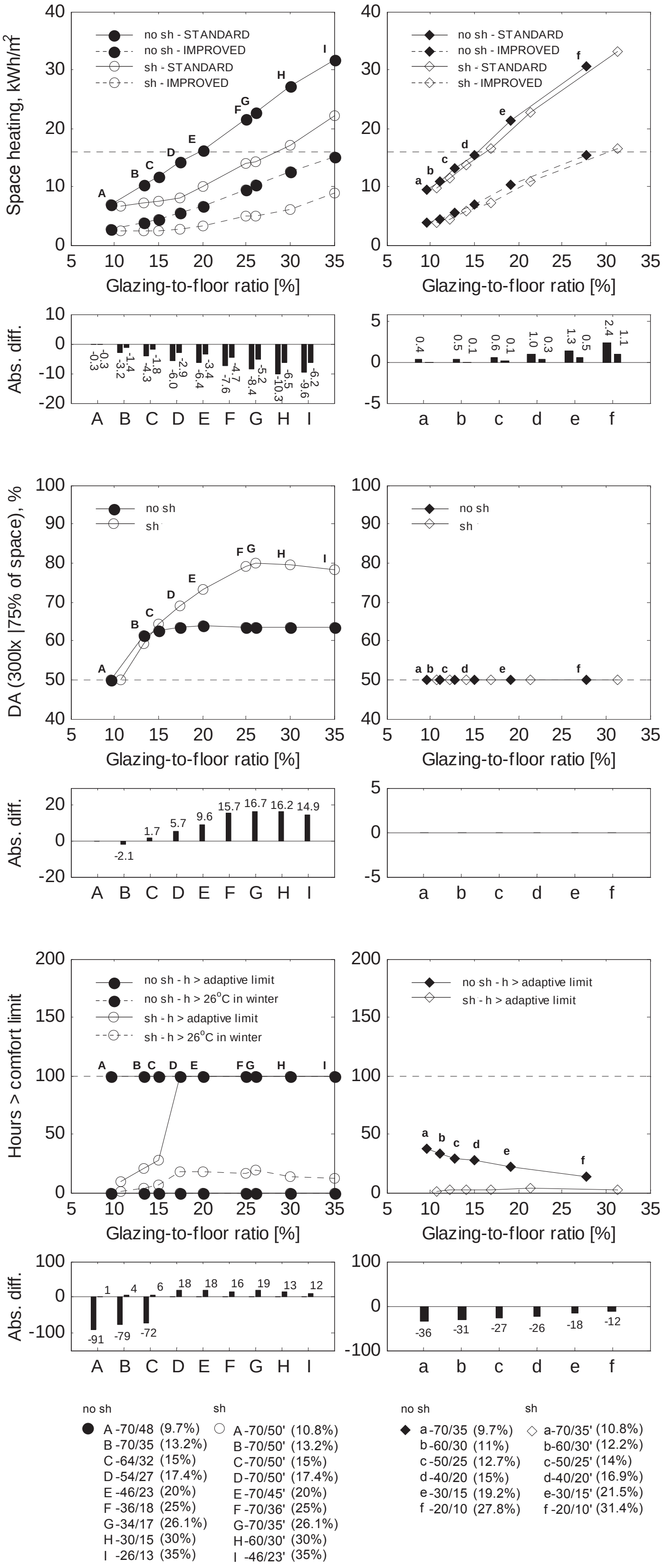


Figure 4: Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading in Copenhagen for the evaluation points A-I (left) and a-f (right). LT, g-value and glazing-to-floor ratio of the evaluation points are listed in the bottom of the figure.

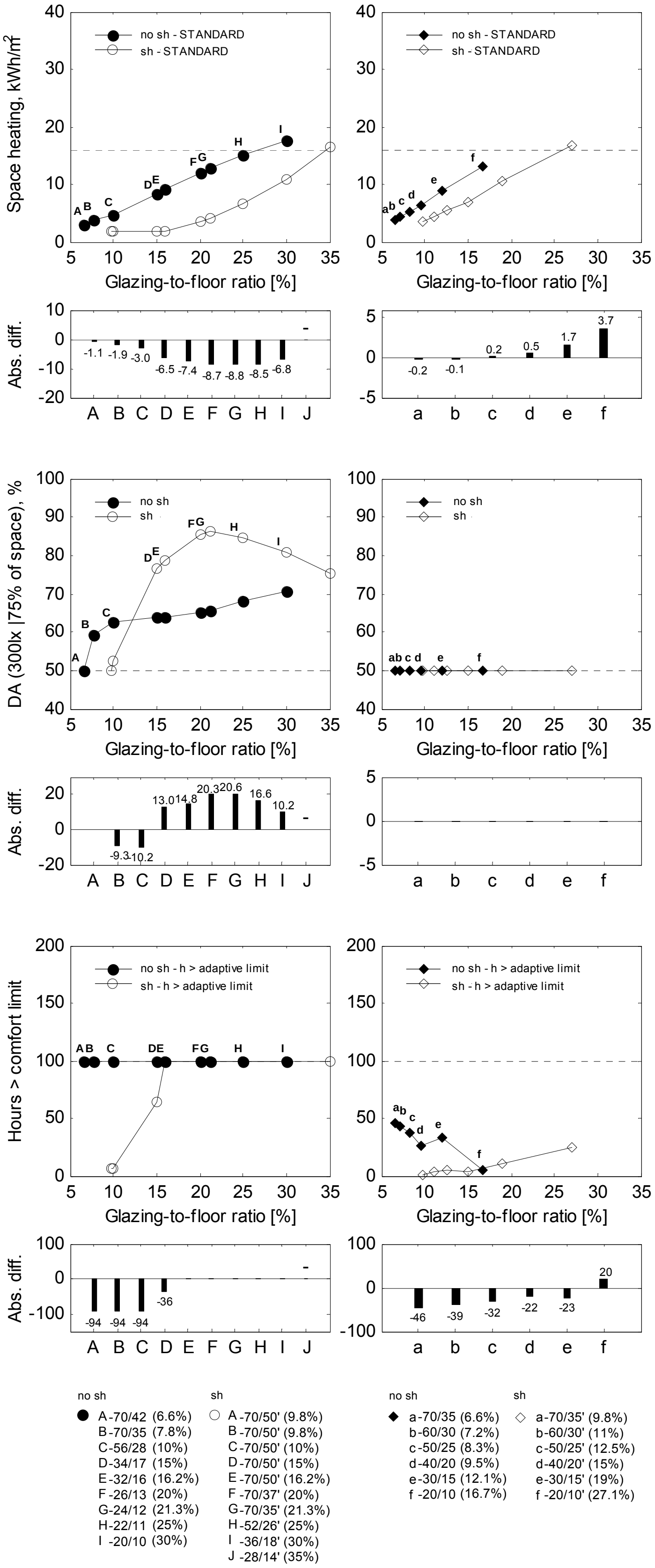


Figure 5: Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading in Rome for the evaluation points A-J (left) and a-f (right). LT, g-value and glazing-to-floor ratio of the evaluation points are listed in the bottom of the figure.

sensitive to a number of factors that depend more on the solution space without shading and the physical limitations of the glazing, than on the increased flexibility found with the shading itself. For example, if a lower maximum g-value had been assumed in the comparisons, there would be no differences in g-value. Similarly, if larger venting rates had been assumed in the comparisons, the g-value of 0.5 (or even higher) would be acceptable for thermal comfort both with and without dynamic shading. Moreover, it should be kept in mind that dynamic shading may increase space-heating demand if not properly controlled. Seen in the light of these considerations, the possibilities of finding a higher g-value with dynamic shading than without were limited.

Similarly, the possibility of using the clear glazing in combination with larger glazing sizes had no advantages in terms of space-heating demand. By studying the development in space-heating demand with shading for the window with standard thermal properties in Copenhagen in the interval A-D (Figure 4, top-left), it may be seen that space-heating demand increased by 1-2 kWh/m^2 when going from the smallest to the largest glazing size. For the window with improved thermal properties in Copenhagen and the window in Rome, glazing size increased space heating considerably less and could be chosen almost freely in this interval. In Rome, the optimum glazing size for space heating was actually slightly larger than the smallest glazing sizes for daylighting without shading (see points a-b in Figure 5, top-right), but these differences would correspond to changes in space-heating demand of less than 0.2 kWh/m^2.

For Rome, where the thermal properties of the glazing studied have some room for improvement, large windows with better thermal properties could potentially reduce space heating. For Copenhagen, however, the results above mean that large windows generally lead to more energy being needed for space heating, even with the very well-insulated windows that are state-of-the-art and standard practice today. Both with and without dynamic shading, the option with the lowest space-heating demand was therefore the glazing with the highest light transmittance dimensioned to just fulfil the daylight target (point A). Since the possibilities of using a higher g-value with shading than without for this option were limited, dynamic shading had almost no potential for improving the optimum space-heating demand of the loft room.

3.2.2. Achievements on space heating for larger glazing sizes

For larger glazing sizes, space-heating demand was significantly lower with dynamic shading than without, due to the increasing differences in maximum g-values for thermal comfort (Figure 4-5, top-left). For very large windows, the use of dynamic shading could save up to 9-10 kWh/m^2 per year, but for this glazing size such comparison is not necessarily meaningful (see Section 3.3). For most glazing sizes in Copenhagen, the space-heating demand of using the standard thermal properties with dynamic shading was approximately 5 kWh/m^2 higher than of using the improved thermal properties without dynamic shading.

Table 5: Achievements on daylighting and thermal comfort with and without dynamic shading for glazing with and without solar-control coating (referred to as 'clear' and 'full solar' as in Figure 3). The evaluation points for which the achievements were found are indicated in brackets, and for daylighting the glazing-to-floor ratios at which the achievements were found are indicated as well.

		No dynamic shade		Dynamic shade	
		Almost clear	Full solar	Clear	Full solar
Percentage of daylight hours with 300 lx in 75% of the space (%)	Rome	50 (A-6.6%)	63 (C-10%)	79 (E-16%)	86 (G-21%)
	Copenhagen	50 (A-9.7%)	63 (C-15%)	70 (D-17%)	80 (G-26%)
Time with excessive temperatures (h)	Rome	100 (A)	At most 50 (a-f)	10 (A)	0 (a-d)
	Copenhagen		At most 40 (a-f)		0 (a-f)

3.2.3. Achievements on daylighting and thermal comfort

If using the clearest glazing possible without dynamic shading (see Point A, referred to as 'almost clear' in Figure 3, top row), daylighting and thermal comfort was just acceptable:

- Illuminances of 300 lx in 75% of the space for 50% of the daylight hours.
- 100 h with operative temperatures exceeding the comfort limit.

By the use of solar-control coating, dynamic solar shading or a combination of both, however, it was possible to find options that improved either daylighting or thermal comfort. These options and the achievements on daylighting or thermal comfort are summarised in Table 5.

From Table 5 it can be seen that the use of optimal solar-control coating alone (see the options referred to as 'full solar' in Figure 3, top row) made it possible to:

- Increase the percentage of daylight hours with sufficient daylighting by 13% in both climates, which corresponds to around 570 h with sufficient daylighting more than targeted.
- Reduce the time with excessive temperatures by at least 50-60 h.

The improvement in daylighting above corresponds to the maximum achievement on daylighting without dynamic shading. This was found at glazing-to-floor ratios of 10% in Rome and 15% in Copenhagen with transmittances of around LT 60% and g-value 0.3 (see point C in Figure 4-5).

The use of dynamic solar shading in combination with clear glazing (see the options referred to as 'clear' in Figure 3, bottom row) made it possible to:

- Increase the time with sufficient daylighting by approximately 700 h and 300 h more than could be achieved without dynamic shading in Rome and Copenhagen respectively.
- Reduce the time with excessive temperatures by approximately 90 h in both climates, which corresponds to 30-40 fewer hours with excessive temperatures than could be achieved without dynamic shading.

The improvement in daylighting above was found at glazing-to-floor ratios of around 16-17%, using glazing with transmittances of LT 70% and g-value 0.5 (see points E and D in Figure 4-5).

Finally, the use of dynamic shading in combination with optimal solar-control coating (see the options referred to as 'full solar' in Figure 3, bottom row) made it possible to:

- Increase the time with sufficient daylighting by approximately 1000 h and 750 h more than could be achieved without dynamic shading in Rome and Copenhagen respectively.
- Eliminate the time with excessive temperatures, which corresponds to 40-50 fewer hours with excessive temperatures than could be achieved without dynamic shading.

The improvement in daylighting above corresponds to the maximum achievement on daylighting with dynamic solar shading. This was found at glazing-to-floor ratios of approximately 20-25%, using glazing with transmittances of LT 70% and g-value 0.35 (see point G in Figure 4-5).

In Copenhagen options with dynamic shading on the comfort limit led to around 20 hours with operative temperatures above 26°C in the winter season (see points D-J, Figure 4, bottom-left). This was not observed in Rome. While the achievements on daylighting and thermal comfort identified above consider options on the limits for either daylighting or thermal comfort, however, the flexibility in the solution space could also be used to find a compromise. If for example, option D in Copenhagen was used with a g-value of 0.35 instead of 0.5 (see the arrow in Figure 3), this would give the same daylighting as for D, while thermal comfort would be significantly improved.

3.3. What could be achieved with dynamic shading when?

If the targeted daylight autonomy of 50% is considered sufficient, the most rational option in terms of both space-heating demand and cost would be to use windows with high light transmittances dimensioned to just meet the daylight criterion (point A). For such options (glazing-to-floor ratios of 9.7% in Copenhagen 6.6% in Rome without shading), dynamic shading had no predictable effect on space heating, so the main benefits of using dynamic shading in this case would be to almost eliminate hours exceeding the comfort limit. If instead using solar-control coating to reduce the time with excessive temperatures by 50-60 h, this would increase space-heating demand by approximately 2-3 kWh/m^2 per year (see space-heating demand of the points A and a in Figure 3, top row).

If it is considered desirable to increase the percentage of daylight hours with sufficient daylighting from the targeted 50% to the approximately 63% that could be achieved both with and without dynamic shading (glazing-to-floor ratios of 10% in Rome and 15% in Copenhagen), this level could be achieved with approximately 3-4 kWh/m^2 per year less space heating and 70-90 hours less exceeding the comfort limit with dynamic shading than without (see point C in Figure 4-5, top- and mid-left). Since there may be no reason to further increase glazing sizes without shading after this maximum for daylighting has been reached, the savings in space-heating demand found for point C may be seen as the largest comparable achievements of dynamic shading on space heating.

If dynamic shading is used as a means of further increasing daylighting by the approximately 750-1000 more hours per year that could be achieved with dynamic shading than without (glazing-to-floor ratios of 20-25%), the fraction of these improvements found with clear glazing (approximately 40% in Copenhagen and 70% in Rome) would cost less in space-heating demand than the maximum daylighting found without shading (see point C). For the window in Rome and the window with improved thermal properties in Copenhagen, the effect of window size was furthermore so small, that all of these improvements could be achieved almost for free compared to the maximum daylighting found without shading (see point G with shading and point C without shading in Figure 4-5, top-left).

4. Conclusions

The more flexible solution space with dynamic shading made it possible to either reduce the time with operative temperatures exceeding the Adaptive Thermal Comfort (ATC) limit by 40-50 hours or increase the time with sufficient daylighting by 750-1000 hours more than could be achieved without dynamic shading. This maximum daylighting was found at glazing-to-floor ratios of around 20-25%, when using a glazing with light transmittance 70% and optimal solar-control coating (g-value 0.35).

Both with and without dynamic shading, the percentage of daylight hours with illuminances of 300 lx or more in at least 75% of the space could be improved from the targeted 50% to around 63% in both Rome and Copenhagen. Up to this point (glazing-to-floor ratios of 10% in Rome and 15% in Copenhagen), dynamic shading had no advantages over permanent glazing solutions in terms of daylighting. With dynamic shading, however, this level could be achieved with 3-4 kWh/m^2 less space heating and 70-90 fewer hours with excessive temperatures. Dynamic solar shading did not affect the possibility of improving the optimum space-heating demand of the loft room in any predictable way. Large windows generally increased space-heating demand, and for windows dimensioned for the targeted daylight autonomy of 50% (glazing-to-floor ratios of 6.6% in Rome and 9.7% in Copenhagen), dynamic shading had limited potential for improving the space-heating demand. Since too high temperatures could also be reduced by 50-60 hours by lowering the g-value at a cost of 2-3 kWh/m^2, the comfort benefit of using dynamic shading in this case would be to eliminate the time with excessive temperatures almost entirely.

5. Outlook

Insofar as the targets for daylighting and thermal comfort used in the present study can be considered humane and reasonable, dynamic shading was not needed. To move closer to an answer on this, more research is needed on the human need for daylighting in homes and on how occupants experience overheating as defined by the ATC model. This would be especially relevant for Rome, where every one hour with operative temperatures exceeding the ATC limit equals several hours with rather high temperatures (see Section 2.3.2). The results may also be sensitive to uncertainties such as the varying and unpredictable internal gains and user patterns in homes. If the venting rates of 3-4 h^{-1} assumed in the comparisons, or even higher, are to be achieved in practice, however, the findings of this study give good reason to assume that glazing with permanent solar control could be used as an excellent means of achieving sufficient daylighting and thermal comfort in nearly zero-energy homes with no compromise on space heating.

The investigation also demonstrated how the use of solar-control coating, both with and without dynamic shading, can be directly linked to quantifiable achievements on either daylighting or thermal comfort. In this study, thermal comfort and daylighting were intentionally evaluated as separate performance parameters with their own value. However, if for example the 570 more hours with sufficient daylighting that were found by using solar-control coating had been converted to electricity use for lighting, this might very well have outbalanced the cost in space-heating demand of 2-3 kWh/m^2 of reducing the g-value from 0.5 to 0.35. This would off course depend on control strategy and power density of the lighting system installed, the use of the room and local energy production systems for electricity and heating. In either case, the balance between daylighting and thermal comfort in nearly zero-energy homes is a challenge that is just as important as lowering the energy use for space heating. Since solar-control coating is a cheap, robust and user-friendly means of improving this balance, with no operational costs, we recommend considering it for this value, rather than excluding it from decisions on proper window solutions due to the cost in space heating. Instead we suggest that the thermal properties of windows for nearly zero-energy homes should be brought to levels where users are free to select the best option for daylighting and thermal comfort.

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