Roof windows in low-energy buildings - Analyses of demands and possibilities for future product development

Gunnlaug Cecilie Jensen Skarning

PhD Thesis

Department of Civil Engineering
2017

DTU Civil Engineering R-369

DTU Civil Engineering
Department of Civil Engineering

Roof windows in low-energy buildings

- Analyses of demands and possibilities
for future product development

Gunnlaug Cecilie Jensen Skarning

PhD Thesis

Department of Civil Engineering
Technical University of Denmark

2017

Supervisors:

Professor Svend Svendsen, DTU Civil Engineering, Denmark
Assistant Professor Christian Anker Hviid, DTU Civil Engineering, Denmark
Karsten Duer, VELUX A/S Hørsholm, Denmark
Morten Møller Mogensen, VELUX A/S Østbirk, Denmark

Assesment Committee:

Associate Professor Toke Rammer Nielsen, DTU Civil Engineering, Denmark
Associate Professor Steffen Petersen, Aarhus University, Denmark
Professor Arild Gustavsen, Norwegian University of Science and Technology, Norway

Roof windows in low-energy buildings
-Analyses of demands and possibilities
for future product development

Cover photo: VELUX A/S

Publisher: Department of Civil Engineering
Technical University of Denmark
Brovej, Building 118,
DK–2800 Kgs. Lyngby

ISBN: 9788778774637
ISSN: 1601-2917

Report: DTU Civil Engineering Report R-369

Preface

This thesis is submitted as a partial fulfilment of the requirements for the Degree of Doctor of Philosophy at the Technical University of Denmark, Department of Civil Engineering. The thesis is the result of more than three years of full-time research on the effect of roof and façade windows on energy, daylighting and thermal comfort in very well-insulated residential buildings.

I am grateful to my supervisor Professor Svend Svendsen and my co-supervisor Assistant Professor Christian Anker Hviid for their guidance and advice throughout the course of this PhD study. My gratitude is also extended to VELUX A/S for their financial support for this research, and to my co-supervisors Morten Møller Mogensen from VELUX A/S in Østbirk and Karsten Duer from VELUX A/S in Hørsholm for their open-minded interest and involvement in the project.

Thanks to all my colleagues in the Section of Building Energy for the good spirit, and special thanks to Matilde Grøn Bjørneboe for the relief it has been to discuss and share big and small challenges in our final project stages.

I would like to thank Lawrence White from the Language Support Centre for proofreading this thesis.

Thanks to my close friend Julie Brønserud for her engagement in any kind of work and life situation, and for proofreading my Danish abstract.

My sincere and deep thanks to my close friends and family who have all supported and motivated me over these years. I'm especially thankful to Nicholai Rudbeck Zickert and Alexander Moen for their invaluable support.

Not least, I would like to thank my parents, sister and brothers for always believing in me and for always being there to strengthen and encourage me.

Kgs. Lyngby, 21st May 2017

Gunnlaug Cecilie Jensen Skarning

Abstract

As part of an ambitious energy policy and strategy for reducing the use of fossil fuels in the European Union, all new buildings are required to consume 'nearly zero-energy' by the end of 2020. This creates a strong need for research in cost-effective solutions and technology that can help balance the goal of a very low energy use with good daylighting and a healthy and comfortable indoor environment. Windows play a very large role in both the energy consumption and the indoor environment of buildings. Roof windows are a particularly efficient daylighting source, which certain types of houses depend on to receive sufficient daylighting in all parts. The development of roof windows with an overall improved performance for use in nearly zero-energy houses might therefore help considerably in the achievement of these goals in a cost-effective way.

The main hypothesis of this research was that the current best standard-practice roof windows can be improved in a way that makes it easier and more cost-effective to realise nearly zero-energy houses with sufficient daylighting and thermal comfort throughout.

This hypothesis was tested through a series of simulation-based investigations focusing on the effect of various combinations of glazing size, thermal properties of glazing, frame and junctions, and transmittance of light (LT) and solar energy (g-value) on energy use, daylighting and thermal comfort.

The effect of roof and façade window parameters was first studied in rooms with windows of a certain slope and orientation to identify the demands and possibilities in various parts of the building. A glazing diagram was developed which made it possible to map and compare the various options that provide sufficient daylighting and thermal comfort. This showed that well-dimensioned façade windows with light transmittances of about 40–70% could provide sufficient daylighting without overheating in the climates of Rome and Copenhagen, as long as they were located in rooms with a reasonable layout for daylighting and appropriate solar-control coating was used on solar exposed glazing. The same was true for sloped and horizontal roof windows with any choice of light transmittance in both climates.

Roof-window thermal properties needed for flexibility were then identified by studying the effect of these options on space-heating demand in rooms representing various parts of a $1^1/_2$-storey house with a simplified floor plan and no interaction of air or heat between zones. This showed how improved roof-window frame constructions and heat loss coefficients of the glazing lower than current standard levels would make it possible to achieve nearly zero-energy consumption with a wider range of options providing sufficient daylighting and thermal comfort, and with increased use of rooms with sloped roof windows oriented north. In Copenhagen, such improvements were found critical for adequate flexibility in building design, while in Rome they were not. Due to the low utilisation of solar gains, such improvements were also generally needed for roof windows in Copenhagen with any orientation to reduce the impact of the choice of window size on space-heating demand.

Comparison of options with and without dynamic shading in a loft room with sloped roof windows facing south in the two climates, showed that dynamic shading made room for considerably more daylighting without overheating than using optimal solar-control coating on its own. However, in both cases, 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 of excessive temperatures as defined by the Adaptive Thermal Comfort model. Moreover, as an option for reducing the optimum space-heating demand, dynamic shading showed limited potential in Copenhagen, while it could have some potential in Rome.

Finally, the performance and cost-effectiveness of various options for improvement were studied for two large single-family houses in Copenhagen with typical floor plans and sloped (Case A) and horizontal (Case B) roof windows. The scope for investment in improved roof windows was identified on the basis of the cost of the insulation not needed in the houses to meet nearly zero-energy requirements with the improved roof windows installed instead of the options that are current best standard-practice. For the specific improvements investigated, this revealed examples of savings in insulation costs that would allow users to pay EUR 50–320 more per m^2 improved roof window than for the products that are best standard practice today. Of these amounts EUR 50–60 were due to improvements in the glazed part alone, EUR 100–300 were due to improvements in the frame constructions, while EUR 320 were due to a relatively simple improvement in the horizontal roof windows, where the addition of a 3-pane glazing at the bottom of the light well considerably reduced the overall heat losses. If manufacturers can make such improvements available at prices within these scopes for investment, nearly zero-energy houses with sufficient daylighting and thermal comfort throughout could be realised in an easier and more cost-effective way.

Resumé

Som led i EU's energipolitik og strategier for at reducere brugen af fossile brændstoffer skal alle nye bygninger være tilnærmelsesvis energineutrale i år 2020. Dette skaber et stort behov for forskning i udviklingen af rentable løsninger og teknologier, som kan bidrage til at balancere målsætningerne om et meget lavt energiforbrug med gode daglysforhold og et sundt og komfortabelt indeklima. Vinduer har stor betydning for både energiforbrug og indeklima i bygninger. Ovenlysvinduer er en særlig effektiv kilde til dagslys, og de er i bestemte typer af huse også nødvendige for at opnå tilstrækkeligt dagslys overalt. Udvikling af ovenlysvinduer med en overordnet forbedret ydelse til brug i huse med et meget lavt energiforbrug kunne derfor tænkes at have et stort potentiale i forhold til at opnå de nævnte målsætninger på en rentabel måde.

Den overordnede hypotese for denne afhandling var, at de bedste ovenlysvinder, der udbydes som standard på markedet i dag, kan forbedres på en måde, som vil gøre det nemmere og billigere at realisere 'nær nul-energihuse' med gode dagslys- og indeklimaforhold.

Denne hypotese blev testet gennem en række undersøgelser baseret på simulering af energi, dagslys og termisk indeklima for forskellige kombinationer af rudestørrelse, transmittanser for lys og solenergi og termiske egenskaber for rude, ramme/karm og samlinger.

Muligheder og behov i de enkelte bygningsdele blev først undersøgt gennem studier af ovenlys- og facadevinduesparametre i rum med vinduer med én bestemt hældning og orientering. I forbindelse med disse studier blev der udviklet et glasdiagram, som gjorde det muligt at kortlægge og sammenligne de anvendelige vinduesløsninger mht. dagslys og termisk komfort. Diagrammet viste, at veldimensionerede facadevinduer med lystransmittanser på omkring 40–70% kunne overholde dagslys- og komfortkriterier i rum med en fornuftig geometri ift. dagslys i både det italienske og det danske klima ved anvendelse af en passende solafskærmende belægning på ruder med direkte solindfald. Det samme var tilfældet for ovenlysvinduer i skråt såvel som i fladt tag i begge klimaer med næsten frit valg af lystransmittans.

De nødvendige termiske egenskaber for ovenlysvinduerne med hensyntagen til forskellig grad af fleksibilitet blev dernæst undersøgt gennem en analyse af opvarmningsbehovet for de anvendelige løsninger mht. dagslys og komfort i rum svarende til forskellige dele af et halvandetplanshus med en forenklet planløsning og uden varmeudveksling mellem zoner. Analysen viste, hvordan ovenlysvinduer med forbedrede ramme/karm-konstruktioner og med varmetabskoefficienter for ruden væsentligt under nuværende standardniveau kan gøre det muligt at imødekomme fremtidige energikrav med en bredere vifte af løsningsmuligheder for dagslys og komfort og ved større inddragelse af rum med nordvendte ovenlysvinduer. I det danske klima var disse forbedringer afgørende for tilstrækkelig fleksibilitet i bygningsdesignet, hvorimod samme krav ikke gjorde sig gældende i Rom. I kraft af den begrænsede udnyttelse af soltilskud i næsten energineutrale huse, var det generelt også nødvendigt at foretage termiske forbedringer af ovenlysvinduerne i det danske klima for at reducere betydningen af vinduesstørrelsen ift. opvarmningsbehovet.

En sammenligning af løsningsmuligheder for vinduer med og uden dynamisk solafskærmning i et rum med skrå sydvendte ovenlysvinduer i de to klimaer viste, at dynamisk solafskærmning gjorde det muligt at opnå mere dagslys ved samme komfort end ved brug af permanent solafskærmende belægning alene. Dog var det i begge tilfælde muligt at opnå dagslys svarende til 300 lx i 75% af rummet i 50–63% af de lyse timer uden mere end 40–100 timer med overtemperaturer i henhold til den adaptive komfortmodel. Endvidere havde dynamisk solafskærmning meget lidt potentiale i forhold til at reducere opvarmningsbehovet i det danske klima, hvorimod dette kan være muligt i Rom.

Til sidst blev ydelse og lønsomhed for forskellige forbedringer af ovenlysvinduerne undersøgt med udgangspunkt i to store enfamiliehuse i det danske klima med typiske planløsninger og henholdsvis skrå (Case A) og horisontale (Case B) ovenlysvinduer. De øvre grænser for at investere i forbedrede ovenlysvinduer blev anslået ud fra prisen på den isolering, som kunne bespares ved at installere de forbedrede løsninger i stedet for de bedste standardløsninger som fås på markedet i dag. Eksempler på konkrete forbedringsmuligheder resulterede i besparelser svarende til, at husejere kan betale 50–320 EUR mere for de forbedrede vinduer per m^2 end for dagens bedste standardprodukter. Af disse beløb knyttede 50–60 EUR sig til forbedringer i selve rudedelen, 100–300 EUR til forbedringer i ramme/karm, og 320 EUR til en relativt simpel forbedring i de horisontale ovenlysvinduer (Case B), hvor tilføjelsen af en 3-lagsrude i bunden af lysskakten kraftigt reducerede det samlede varmetab. Hvis det er muligt at sætte produkter med tilsvarende forbedringer på markedet til merpriser inden for disse beløb, vil ‘nær nulenergihuse’ med gode dagslys- og indeklimaforhold kunne lade sig realisere på en nemmere og billigere måde end i dag.

Contents

Chapter 1

Introduction

1.1 Background

1.1.1 Nearly zero-energy targets

Improving the energy performance of buildings is a priority area in European Union (EU) energy policy and strategy for reducing the use of fossil fuels. In 2010, the European Parliament and the Council of the European Union adopted a recast of the Energy Performance of Buildings Directive which stated that by the end of 2020 all new buildings will be required to consume 'nearly zero' energy (EU, 2010). It is the responsibility of the member states to establish cost-optimal nearly zero-energy requirements for their buildings in accordance with future energy prices, discount rates and local energy production systems. In Denmark, the goal is that by 2035 all electricity and heat supply should be based on renewable energy sources in preparation for a completely fossil-free energy and transport system by 2050 (Danish Ministry of Climate, Energy and Building, 2011). This is to be achieved through a combination of a cleaner energy supply and reduced consumption, and to accelerate development towards buildings with a very low energy use, the Danish building regulations have implemented a 'low energy class 2020'. This class specifies clear requirements for maximum energy use in nearly zero-energy buildings, which will apply for all new buildings in Denmark from 2020. For residential buildings, the new requirements mean that the annual primary energy usage, which covers space heating, cooling, domestic hot water and electricity for pumps and ventilation fans, should not exceed 20 kWh/m^2 (BR, 2016). But it is also part of the ambitions that the new buildings should be solutions of high quality, with good daylighting and a healthy and comfortable indoor environment (Danish Energy Agency, 2016). This creates a strong need for research in cost-effective solutions and technology that can help balance the goal of very low energy use with indoor conditions that meet human needs and promote well-being.

Heat transfer through windows is central for both space-heating demand and thermal comfort (or cooling demand). At the same time, windows determine the amount and distribution of natural daylight entering a space. So windows have a very large impact on both the energy consumption and the indoor environment in buildings. Windows need to be optimised to meet energy, daylighting, and thermal comfort requirements all at the same time in nearly zero-energy houses if they are to achieve an indoor environment of high quality throughout. Furthermore, the three main glazing parameters governing window performance on these issues are closely related. These are the heat loss coefficient (U-value), the solar energy transmittance (g-value) and the light transmittance (LT). The development of cost-effective window products with an overall improved performance therefore requires careful consideration of the impact of these three parameters on energy, daylighting and thermal comfort combined.

1.1.2 Development of roof windows with improved performance

Roof windows are known to provide about twice as much daylighting as façade windows per area of window (Dubois et al., 2003 and Johnsen, Dubois and Grau, 2006). Under perfectly overcast conditions, where the sky is considerably brighter at zenith than near the horizon, horizontal roof windows can receive almost three times as much daylight as vertical windows of the same size. Roof windows also allow even daylight distributions due to their flexibility in position. All this makes roof windows a particularly efficient source for natural daylighting. Moreover, without the use of advanced redirecting devices, façade windows with normal head heights can only provide sufficient daylighting in areas within about 4–5 m of the façade (O'Connor et al., 1997). With the tendency towards increasing floor areas in homes, roof windows may therefore become increasingly important in the future, because large parts of various types of compact houses will depend on roof windows to receive sufficient daylighting at all.

This means that there may be a large potential in the development of roof windows with an overall improved performance for use in nearly zero-energy houses. This research examined the possibilities of developing roof windows with an optimal balance between U-value, g-value, and light transmittance for use in these buildings. If such options for improving roof windows can be identified, they could lead to a new generation of flexible and cost-effective building components that would make it easier to realise nearly zero-energy houses with a well-lit and pleasant indoor environment.

1.2 Aim and hypotheses

The aim of this research was to identify development options for roof windows that might make it easier and more cost-effective to realise nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces.

1.2.1 Main hypothesis (MH)

The main hypothesis (MH) was as follows:

The current best standard-practice roof windows can be improved in a way that makes the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces easier and more cost-effective.

1.2.2 Sub-hypotheses (SH1–SH6)

The main hypothesis was tested using an approach in which options for improving the windows were first identified by studying energy, daylighting and thermal comfort in individual building parts. Their performance and cost effectiveness were then tested in complete houses.

The following sub-hypotheses (SH1–SH6) are closely related to this approach and support the main hypothesis:

- SH1: *The space-heating demand of nearly zero-energy houses can be represented by a few key parameters.*
- SH2: *Improvements in the energy performance of façade windows can be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces.*
- SH3: *Improved roof-window frame constructions and glazing U-values lower than current standard levels can increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces.*
- SH4: *Dynamic solar shading can make room for more daylighting without overheating, but cannot reduce energy use for space heating.*
- SH5: *The relative importance of roof-window parameters found at room level holds true at building level.*
- SH6: *Improved roof-window frame constructions and glazing U-values lower than current standard levels would make it possible to build nearly zero-energy houses in a more cost-effective way.*

1.2.3 Research questions (Q1–Q6)

When rephrased, the sub-hypotheses SH1–SH6 make up the research questions (Q1–Q6) listed below. These research questions are an output from the state-of-the-art review in Chapter 2, and they will be explained in more detail in Section 2.3.

- Q1: *Can the space-heating demand of nearly zero-energy houses be represented by a few key parameters?*
- Q2: *Can improvements in the energy performance of façade windows be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces?*
- Q3: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces?*
- Q4: *Can dynamic solar shading make room for more daylighting without overheating? Can dynamic solar shading reduce energy use for space heating?*
- Q5: *Does the relative importance of roof-window parameters found at room level hold true at building level?*
- Q6: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels make it possible to build nearly zero-energy houses in a more cost-effective way?*

1.3 Selected investigations and related papers

A sequence of five simulation-based investigations focusing on the effect of various combinations of window size and glazing properties on energy, daylighting and thermal comfort were carried out to answer the research questions above, following the workflow sketched in Figure 1.3.1.

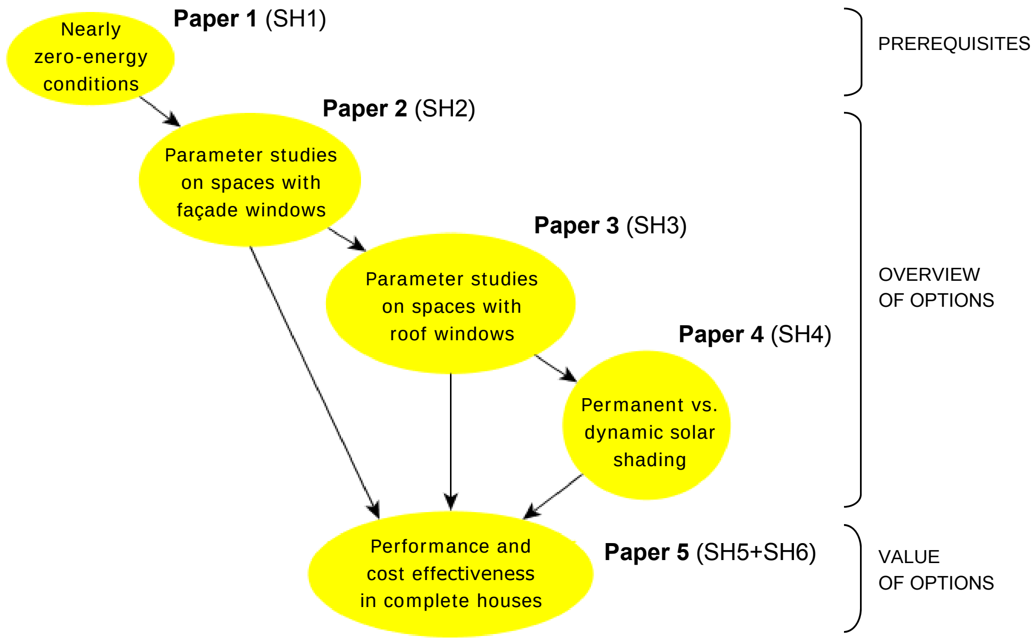


Figure 1.3.1. *Sketch of workflow, showing the five investigations described in Papers 1–5, which were carried out to test the sub-hypotheses SH1–SH6.*

The investigations cover one main sub-hypothesis each, except for the last one, which covers sub-hypotheses SH5 and SH6. However, results from most of the investigations will also be used to discuss other sub-hypotheses. As indicated in the figure, each of the five investigations is described in one of the five papers P1–P5 that form the basis for this thesis. The papers are appended at the end of the thesis, and a complete list of papers with titles, authors and publication details can be found in the table of contents. For the four journal papers, the date of acceptance is given in brackets.

A brief summary of the investigations described in the five papers is given on the following two pages.

1.3.1 Nearly zero-energy key parameters (P1)

Paper 1 (P1), "*Investigation and description of European buildings that may be representative for 'nearly zero' energy single-family houses in 2020*", proposes a set of key parameters and properties that can be used to model the nearly zero-energy conditions in which future windows are to be used. This set was established for the three significantly different European climates of Rome, Bratislava and Copenhagen. The output from this investigation forms the basis for studying the effect of roof and façade windows on energy, daylighting and thermal comfort in more detail in Papers 2–4 based on strategically selected rooms in nearly zero-energy houses.

1.3.2 Parameter studies on façade windows (P2)

Paper 2 (P2), "*Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses*", looks into how basic façade window parameters affected energy, daylighting and thermal comfort in rooms with various geometries in nearly zero-energy houses located in Copenhagen. Knowledge about appropriate façade window solutions is a prerequisite for studying roof windows. The investigation provided information about both window properties and room geometries that would be useful in nearly zero-energy houses with façade windows.

This paper also presents a new tool, the glazing diagram, which has been central throughout this research. This diagram makes it possible to evaluate the effect of various window parameters within a solution space formed by criteria for daylighting and thermal comfort.

1.3.3 Parameter studies on roof windows (P3)

Paper 3 (P3), "*Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe*", uses the glazing diagram from Paper 2 to discuss the usefulness of possible approaches for improving roof and façade windows based on selected rooms in the middle section of a 1½-storey house with a simplified floor plan in two locations: Rome and Copenhagen. The paper discusses the importance of basic window parameters in different parts of the building section considered, and pays special attention to the heat losses through the frames and junctions of the roof windows. The paper sketches the increased flexibility and related possibilities that could open up with considerably improved frames and junctions and heat loss coefficients of the glazing lower than current best standard-practice levels.

1.3.4 Permanent vs. dynamic solar shading (P4)

The use of dynamic solar shading may significantly change the solution spaces for the roof windows, and could thus also change the conclusions about the most useful options for improvement.

Paper 4 (P4), "*The effect of dynamic solar shading on energy, daylighting and thermal comfort in a nearly zero-energy loft room in Rome and Copenhagen*", therefore looks critically into what the change in the solution space when a dynamic solar shading device is applied would mean for potential achievements on energy, daylighting and thermal comfort. The potential achievements with dynamic shading were then compared with the potential achievements by using solar-control coating on its own. The investigation was carried out for a loft room in the middle section of the $1^1/_2$-storey house studied in Paper 3 for the two climates of Rome and Copenhagen.

1.3.5 Performance in complete houses (P5)

Paper 5 (P5), "*The cost efficiency of improved roof windows in two well-lit nearly zero-energy houses in Copenhagen*", tests the performance of various options for improving the roof windows to beyond current best standard-practice for two large single-family houses with typical floor plans. These were a $1^1/_2$-storey house with sloped roof windows in the upper storey, similar to the house studied in Papers 3–4, and a quadratic 1-storey house with horizontal roof windows in the core areas. Both houses depend on roof windows to achieve sufficient daylighting in all parts. The investigation was carried out only for Copenhagen, where improvements were found to be most needed.

The effect of the individual roof-window parameters at building level was investigated in both houses and the scope for investing in various types of improved roof windows was identified. The scope for investment was determined based on the cost of the insulation not needed in the two houses to meet the nearly zero-energy requirement with the improved roof windows installed instead of the current best standard-practice roof windows.

1.4 Scope

The scope of this research was limited to buildings for residential use, with the main focus on new nearly zero-energy single-family houses in Denmark. All the investigations were therefore carried out from a Danish perspective, but some of the investigations also include analyses for other locations in Europe to put the findings into a broader climate context. For instance, Rome was used as an example of a southern European climate. The energy targets, building types, etc. used in these analyses are not necessarily representative of the respective countries, but the analyses can provide relevant information about window options in these climates if similar space-heating demands, etc. are aimed at.

1.5 Structure of thesis

Chapter 1 is the introduction to the aim, main hypothesis, and the five investigations carried out to test the six sub-hypotheses.

Chapter 2 reviews existing research on windows for residential use, and identifies the knowledge gaps that form the starting points for each of the five investigations carried out to evaluate the hypotheses.

Chapter 3 introduces the performance criteria for energy, daylighting and thermal comfort used throughout the various investigations, the simulation tools and two methods which have been central:

1. The *glazing diagram* used in **Papers 2–4** to map and compare useful options for daylighting and thermal comfort.
2. The method used in **Paper 5** to *determine the scope for investment* in improved roof windows.

Chapter 4 provides an overview of the set-up and assumptions for the five investigations.

Chapter 5 presents the findings from each of the investigations along with relevant methodology.

Chapter 6 discusses the answers to the research questions Q1–Q6 based on these findings.

Chapter 7 concludes on the sub-hypotheses SH1–SH6 and on the main hypothesis, and provides recommendations and suggestions for future work.

Chapter 2

State of the art

The first part of this chapter reviews existing research on the effect of window size and properties on space-heating demand and current approaches to solar shading. The intention of this review is to highlight the findings on these aspects that form the background for the present research. The review is mainly related to the thermal performance of windows; this has so far been the main focus in research on windows for residential use. The second part of the chapter identifies the gaps in knowledge that form the basis for the each of the five investigations carried out to test the sub-hypotheses SH1-SH6. This part refers both to the review and to other relevant research.

2.1 Effect of window size and properties on space-heating demand

2.1.1 Research on lightly insulated houses

The first efforts to reduce the energy consumption generated by windows in residential buildings focused on improved U-values and reduced size (Marsh, Larsen and Kragh, 2010). Later, attention was drawn to how free solar heat gains through windows could be used to reduce space-heating demand. In lightly insulated residential buildings, this was found to have a rather significant potential, which turned the focus towards large and clear south-facing windows to maximise solar gains. This is still a widespread common-sense understanding of low-energy windows. Research on windows focused on identifying options with an energy-neutral performance, known as 'zero-energy windows', or options that provide more energy than they use, also referred to as windows with a positive 'net energy gain'. The following paragraphs give some examples of the effect of window size and other properties on space-heating demand in lightly insulated houses to illustrate the interdependency of the parameters and to provide research-based background for the results from research on very well-insulated houses described in Section 2.1.2.

Window properties needed for energy-neutral performance

Studying a lightly insulated single-family house in the heating-dominated climate of Madison (space-heating demand of around 150 kWh/m^2 per year), Sullivan and Selkowitz (1985b) identified the maximum glazing U-values (U_g) that gave a positive net energy gain as a function of window size, orientation and shading coefficient (SC). For a primary south-facing window area ranging from the minimum to the maximum sizes possible, they found that glazing with U-values of up to 2.5–3.3 W/m^{2}K was energy-neutral if combined with an SC of 0.7, which is equivalent to a solar energy transmittance (g-value) of about 0.6. The maximum glazing U-values for the primary window area facing east were 1.4–1.9 W/m^{2}K, while they were 0.75–0.9 W/m^{2}K for the window area facing north. For the same house, Sullivan et al. (1995) found that an argon-filled double pane low-emissivity glazing with a U_g of 1.7 W/m^{2}K and a g-value of 0.74 resulted in a positive net energy gain whether oriented south, east or west.

Optimum window area facing south

For the same climate of Madison, Sullivan and Selkowitz (1985b) also identified the optimum window area facing south as a function of glazing U-value and shading coefficient (SC). Their study makes it clear that the optimum window area depends considerably on the properties of the glazing. Large window areas were far from an advantage in all cases. However, for glazing with an SC of 0.7 and a U_g below 1.8 W/m^{2}K (which is considerably better than the glazing found above to be just neutral), the optimum window area facing south exceeded the maximum size physically possible. This meant that it could be concluded that south-facing windows resulted in less energy being used for space heating than north-facing windows and should preferably be as large as possible for certain types of good low-energy double glazing available. Seen in this light, the common-sense acceptance of large and clear solar-exposed glazing in low-energy architecture had some hold in research for lightly insulated buildings. However, in discussion about the effect of large solar-exposed glazing on residential space heating in general, it is important to distinguish between the following two situations:

- The situation where increasing the solar-exposed glazing area actually reduces the space-heating demand.
- The situation where increasing the solar-exposed glazing area only reduces space heating because it makes up a larger *fraction* of the total glazing area (i.e. there is less glazing facing other orientations).

These two situations are easily mixed up. The first is only true for certain glazing types, while the latter may reduce daylighting and thermal comfort.

Demands to windows in houses with even window distribution

Studying the effect of window size in a different way, Sullivan et al. (1995) looked into whether various window types lead to net energy gains when the window area was evenly distributed across all façades and increased simultaneously. This study showed that if the equally distributed glazing area was more than 15% of the floor area, slightly better glazing than the argon-filled double pane low-emissivity glazing with a U_g of 1.7 W/m^{2}K and a g-value of 0.74 would be needed to achieve an overall positive net energy gain. On the other hand, the study showed how a number of better glazing types would allow the window area to be increased to 30% of the floor area and still result in a positive net energy gain.

Arasteh et al. (2007) studied the effect of various combinations of window U-value and g-value on space heating and cooling in a slightly larger single-family house with windows corresponding to 15% of the floor area distributed equally on all façades. Their aim was to identify the properties needed for windows to have an energy-neutral performance in average houses. In the heating-dominated climate of Minneapolis (space-heating demand of around 130 kWh/m^2 per year), they found that U-values above 1.1 W/m^{2}K would be energy neutral in terms of space heating if combined with sufficiently high g-values (approximately 0.6 for the window in total). This would require the use of solar shading to minimise cooling needs. For static solutions to be energy neutral for heating and cooling in total, however, they pointed out that windows with U-values lower than 0.68 W/m^{2}K and g-values as high as possible (around 0.4–0.5) would be needed in future buildings.

2.1.2 Research on very well-insulated houses

A number of studies have shown that the characteristics determining the effect of windows on space-heating demand change with insulation level. This section first describes such findings for colder climates in Europe and then highlights the main findings for climates in southern Europe.

Findings for colder climates in Europe

Inanici and Demirbilek (2000) investigated the optimum window area facing south as a function of insulation thicknesses and building aspect ratio for various climates in Turkey. For a rather lightly insulated residential building in the cold region of Erzurum (space-heating demand of around 170 kWh/m^2), large windows facing south generally reduced space-heating demand. With increasing insulation thicknesses, however, they found that the optimum window area facing south decreased.

Bülow-Hübe (2001) studied the window properties needed for a neutral effect on space heating at various levels of insulation for a single-family house in Sweden. The house had a total window area corresponding to 15% of the floor area, of which about 95% was facing south and east. The study showed that, the higher the overall insulation level of the house was, the lower were the maximum U-values needed for the windows to have an energy-neutral effect. With the house insulated in accordance with requirements from the 1960s in the climate of Stockholm (space-heating demand of around 130 kWh/m^2), she found that windows with a maximum U-value of 1.6 W/m^{2}K (U_g = 1.25 W/m^{2}K and g-value = 0.6) had a neutral performance. Given the large solar-exposed glazing fraction in the house, these findings correspond well with the properties highlighted in Section 2.1.1. With the house insulated in accordance with newer and future scenarios, however, the following considerably lower maximum window U-values (U_w), with correspondingly lower g-values, were needed:

- 2000-scenario (space heating of around 50 kWh/m^2): 1.0 W/m^{2}K
- 2020-scenario (space heating of around 15 kWh/m^2): 0.7 W/m^{2}K

Detailed plots from the study show how these changes were due to the shorter heating seasons found when reducing the space-heating demand of the house, which led to less useful solar gains in the remaining months.

Persson, Roos and Wall (2006) investigated the effect of window size and distribution on space-heating and cooling demands in a passive house in Sweden with the same space-heating demand as the best-insulated scenario above (around 15 kWh/m^2 per year). The house had window U-values similar to those that Bülow-Hübe (2001) found to be energy-neutral for this insulation level, and the total window area in the house was about 16% of the floor area. Of this, a very large fraction was facing south and the rest north. The study showed that if this house was rotated by 180° so that the largest window area was instead facing north, space-heating demand would be increased by 3.5 kWh/m^2. Based on this finding, they suggested that windows in very well-insulated houses can be distributed more evenly without a large impact on space heating. Moreover, the study showed that the changes in space heating due to the rotation were almost entirely due to the increased window area facing north, while the effect of decreasing the south-facing window area was very small. By varying the size of the south-facing window area on its own, they found that reducing this area in fact slightly improved space-heating demand, so that the optimum window area facing south was somewhere between the original size and a reduction by 50%. Within this interval, the changes were of a magnitude of 0.1–0.2 kWh/m^2. Detailed plots from a cold sunny day show how the solar gains from the smaller windows were enough to cover all the heating needs.

While the large south-facing windows were almost neutral in terms of space heating, the rather small north-facing windows in the house were responsible for about 6 kWh/m^2 more energy being consumed by the house with windows than without. So it might be concluded that moderate solar gains from south-facing windows are significant. However, in buildings with such a low space-heating demand, only a very small amount of the solar gains are useful.

Looking further into this topic, Vanhoutteghem and Svendsen (2014) studied the effect of window type, size and distribution on space-heating demand in a very well-insulated single-family house in Denmark. Insulated in accordance with Danish 2020-requirements (space-heating demand of around 10 kWh/m^2), this house had a glazing area corresponding to about 15% of the floor area, of which 63% faced south and the rest mainly north. The windows had triple glazing with a U_g of 0.7 W/m^{2}K and a g-value of 0.48. The study showed that the largest window fraction could face north or the windows in the house could be distributed more evenly with almost no impact on space-heating demand. The optimum total window area in the house was about 15–20% of the floor area irrespective of distribution. Furthermore, the study showed that solar-control coating could be used on the south-facing windows without affecting the space-heating demand significantly. The g-value of the south-facing windows could be reduced from 0.48 to 0.33 with almost no effect on the space-heating demand. This corresponds to around the maximum possible reduction in the solar energy transmittance without reducing the light transmittance of the glazing (also referred to as 'ideal solar-control coating' throughout this thesis). If the g-value was further reduced to 0.24, which would require reduction in the light transmittance at the same time, space-heating demand would increase by 1–2 kWh/m^2. These findings support the conclusions from the previous studies on the reduced need for solar gains in very well-insulated houses. In addition, they indicate that the effect of high g-values on space-heating demand tends to diminish beyond a certain limit.

To summarise

Existing research on the effect of windows on space-heating demand in colder climates in Europe has indicated that for very well-insulated houses:

- Windows with considerably better thermal properties are needed for windows to result in a net energy gain.
- The optimum south-facing window area is smaller than expected from experience in lightly insulated houses, even with the best standard-practice glazing types available today.
- The savings in space heating from increasing the g-value tends to diminish after a certain value.

Findings for climates in southern Europe

Studying a narrow and well-insulated two-storey house with windows mainly in one façade, Gasparella et al. (2011) looked into the effect of window size and orientation in the European climates of Nice, Rome, Milan and Paris. For the types of double and triple glazing studied, they found that increasing the window area facing south always reduced space-heating demand. With the best performing high-gain triple glazing ($U_g = 0.7$ W/m^{2}K and g-value = 0.59), increasing the window area from 16% of the floor area to 40% reduced the space-heating demand by around 4 kWh/m^2. This was for the climate of Milan, Italy (space-heating demand of 20–40 kWh/m^2), which they gave as representative of similar heating and cooling trends also in the other climates. For double glazing with a U_g of 1.1 W/m^{2}K and a g-value of 0.61 oriented east/west, changes in window size had almost no effect on space-heating demand. The same was true for the best triple glazing oriented north. They also pointed out that it is largely the solar energy transmittance that determines whether double or triple glazing has the best winter performance in these climates. Maximum requirements for the g-value should therefore be set with care. However, triple glazing reduced winter peak loads the most in all cases, and the effect of window size and g-value on the cooling demand was always considerably larger than on the heating demand.

Albatici and Passerini (2011) studied the effect of window size and orientation for various window types in four different climates in Italy, using the quasi-stationary monthly method in EN ISO 13790. They found that increasing the glazing size facing south reduced space-heating demand in all climates with a window U-value of 2.2 W/m^{2}K. This value corresponds to the Italian prescribed maximum U-values. For east- and west-oriented façades, windows with a U-value of at most 1.4 W/m^{2}K were needed to find an optimum size, while a U-value of 1.2 W/m^{2}K would be needed for increased window size to reduce space-heating demand at any size. All U-values studied assumed a g-value of 0.67, and the annual space-heating demand of the building studied in the climate of Trento (which is close to Milan) was about 10–30 kWh/m^2.

To summarise

Existing research on the effect of windows on space-heating demand in mixed climates in southern Europe has indicated that for well-insulated houses:

- South-oriented windows with today's double and triple glazing tend to reduce space-heating demand more, the larger they are.
- Windows better than double glazing with a U_g of 1.1 W/m^{2}K and a g-value of 0.6 would generally lead to large architectural freedom in the choice of windows in the various orientations and reduce peak loads.

2.1.3 Knowledge based on simplified methods

Various simplified methods have been developed to make it easier to select windows and glazing with the best combinations of U-value and g-value for space-heating demand. In Denmark, simplified formulas for the calculation of the net energy gain (*NEG*) through roof and façade windows (BR, 2017) have been derived from comparisons of degree hours and total amounts of solar irradiation on surfaces with various slopes and orientations over a fixed heating season (T. R. Nielsen, Duer and Svendsen, 2000). For a heating season with 90.36 degree hours (in kKh), the solar irradiation on, for example, a south-oriented façade window would be 301.7 kWh/m^2 in total (after accounting for obstructions by a factor of 0.7). Increasing the g-value of this window by 0.1 would then reduce space-heating demand by 3.3 times more than if the U-value of the window was decreased by 0.1 W/m^2K.

The formulas derived using the above method showed good accuracy when tested against simulations for a lightly insulated single-family house (T. R. Nielsen, Duer and Svendsen, 2000). This indicates that most of the solar gains could be utilised in such houses. Later, a shorter heating season of 74 kKh was proposed to better represent the conditions in houses with a lower space-heating demand (Svendsen, 2011). For very well-insulated residential buildings, however, the method is not suitable, even if combined with a shorter heating season, because it assumes that solar gains can be utilised following a linear relationship with space-heating demand decreasing as the g-value increases. Moreover, the net energy gain formulas derived using this method are misleading for energy-rating purposes because they favour windows with g-values as high as possible with no regard for thermal comfort.

Simplified methods can, however, give an indication of how changes in the U-value and g-value would theoretically affect space-heating demand if all solar gains are utilised, and the relative effect of the two parameters may be seen as a measure for the utilisation of solar gains in lightly insulated houses. Table 2.1.1 shows the relative effect of increasing the g-value compared to decreasing the U-value in accordance with the above simplified method for windows and glazing with various slopes and orientations, and for a one-zone house with windows evenly distributed between facing north and south. The table also shows how the relationships change when going from the original heating season to the shorter heating season suggested in Svendsen (2011).

If we apply the same method to houses with typical window distributions in southern Europe, changes in the g-value would have about 5–7 times the effect of changes in the U-value for façade windows and 8–12 times the effect for roof windows (Kragh, Laustsen and Svendsen, 2008). In contrast, these relationships in Denmark were about 2 and 3–4.

***Table 2.1.1**. Effect of increasing the g-value by 0.1 compared to that of decreasing the U-value by 0.1 W/m^{2}K as found using the simplified methods for calculation of the net energy gain from windows in Denmark. The relationships shown for façade windows include compensation for obstructions by a factor of 0.7.*

Window slope and orientation		Original heating season (24/9–13/5)	Shorter heating season[1)]
Façade windows 90°	S	3.3	2.4
	N	0.8	0.6
	E/W	1.8	1.3
	Average N/S	***2.1***	***1.5***
Roof windows 45°	S	5.7	4.1
	N	1.5	1.1
	E/W	3.4	2.5
	Average N/S	***3.6***	***2.6***

1) These values are estimates based on a projection of the values for the original heating season onto the shorter heating season, using the change in relationship found in Svendsen (2011).

The energy rating system for façade windows developed for the Italian climate by Maccari and Zinzi (2001) using regression analyses rates the g-value as 3.4 times as important as the U-value for space-heating demand.

Manz and Menti (2012) have since proposed a variation of the simplified degree hour method, in which only the ratio of degree hours to irradiation in the month of December is considered. This month was generally found to have the largest temperature differences over solar irradiation potentials in all the eight European climates studied. Based on this method, the following relative importance of increasing the g-value compared to decreasing the U-value was found for vertical surfaces with different orientation in the climates of Stockholm and Rome:

- Stockholm: 1.5 (S), 0.2 (N), 0.4 (E/W) and 0.9 for the average N/S.
- Rome: 11.1 (S), 1.7 (N), 4.0 (E/W) and 6.4 for the average N/S.

These ratios tell us how many times larger the U-value should be than the g-value for a window or glazing to have a positive effect on space heating in December. For example, double glazing with a U_g of 1.1 W/m^{2}K and a g-value of 0.6, which gives a ratio of U-value to g-value of 1.8, would be close to energy-neutral for all orientations in Rome, while this would at no point be the case in Stockholm. Here, triple glazing with about equal U-value and g-value, on the other hand, would be positive facing south and close to neutral for the average of N/S. As with the other simplified methods, this method assumes full utilisation of solar gains, but since it is based on only the worst case month, full utilisation is more likely than with a method based on the heating season as a whole. To some extent the results from using this method agree with the simulation-based findings for Sweden and Italy reported in Section 2.1.2.

2.2 Windows and solar shading

Overheating and considerable cooling needs can be major problems in very well-insulated residential buildings. Even in colder climates in Europe, such as in Denmark, studies by for example Larsen and Jensen (2009) and Brunsgaard, Knudstrup and Heiselberg (2012) have identified severe problems of overheating in both the summer period and the transitional seasons between winter and summer. Furthermore, studies on energy use for space heating and cooling in various European climates, e.g. by Gasparella et al. (2011), Persson, Roos and Wall (2006), Jaber and Ajib (2011) and Du, Hellström and Dubois (2014), have shown that the choice of window size and g-value is generally much more critical for cooling than for heating. And when cooling needs are taken into account in lightly insulated houses, the optimum window area facing south was found to be much smaller (Sullivan and Selkowitz, 1985b and Marsh, Larsen and Kragh, 2010).

2.2.1 The questionable need for dynamic shading

Dynamic solar shading is commonly suggested as a means of reducing such problems of overheating, while preserving high access to daylight and solar irradiation when needed. For example, studies by Apte, Arasteh and Huang (2003), Arasteh et al. (2007), Gugliermetti and Bisegna (2007), Gasparella et al. (2011) and Ihm et al. (2012) have suggested the use of dynamic solar shading rather than permanent shading solutions mainly to maintain the benefits of large solar gains in the winter. Other studies have focused on dynamic solar shading as a means of balancing the need for sufficient daylighting with thermal comfort. In a house called 'Home for life' (Foldbjerg and Asmussen, 2013), which was designed and constructed in Denmark in accordance with Active House principles (Active House Alliance, 2013, 2015), an average daylight factor of 5% could be achieved without overheating using dynamic shading combined with effcient venting. This was with overheating being evaluated on the basis of the Adaptive Thermal Comfort (ATC) model (see Section 3.1.3). Similarly, in a systematic parameter study (Petersen, 2015) on window size, user patterns and cooling strategies in future homes in Denmark based on the same daylight target, Petersen doubts that it is even possible to achieve adequate daylighting in very low-energy houses, unless dynamic solar shading is applied to reduce overheating and thermal comfort is evaluated in accordance with the ATC model. Vanhoutteghem and Svendsen (2014), on the other hand, question the importance of dynamic solar shading in houses with a very low space-heating demand, because such houses have a reduced need for solar gains. They suggest that solar control coated glazing with lower g-values and high selectivity for daylighting could be used to prevent overheating in such houses without critically affecting space-heating demand (see also Section 2.1.2).

Based on their study of total energy use with various combinations of U-value and g-value in a lightly insulated house in the USA (see Section 2.1.1), Arasteh et al. (2007) concluded that dynamic solar shading has the largest potential in mixed climates. Here, the use of dynamic shading considerably reduced cooling needs in the summer, while high access to solar gains in the winter was important for reducing space-heating demands. In such climates, they found that dynamic control of solar gains was more important for achieving an energy-neutral performance of the windows than further lowering the U-values. But in heating-dominated climates, they concluded that the use of windows with high g-values and dynamic solar shading was only one approach to energy-neutral windows, while another strategy would be to focus on developing windows with very low U-values. Even with g-values as high as possible, the g-values typically achieved for these windows would be low enough to keep cooling needs down.

2.2.2 Research considering low g-values for shading

Tsikaloudaki et al. (2015) studied the effect of various types of window with high and low g-values on cooling demands and total energy use in rooms in better insulated residential buildings in the Mediterranean region of Europe (space-heating and cooling demands of about 30–40 kWh/m^2 each). For the same window types, Tsikaloudaki et al. (2012) looked into the effect of different levels of dynamic shading on cooling demands. For the shading strategy investigated (irradiation set-point of 300 W/m^2 and shading factor of 0.15 at the lowest), they found that the use of dynamic shading did not reach the same efficiency as the use of permanently low g-values. With g-values in the range of 0.3–0.4, however, the cooling demands resulting from moderately large windows held reasonable levels. When these g-values were combined with U-values of 1.37 W/m^2 or below, the same was true for the energy use for heating and cooling in total. If glazing with a U-value of 0.72 W/m^2 and a g-value of 0.4 was used, it was also possible to find an optimum south-facing window area for total energy use in the range of 13–25% of floor area. South-facing windows with a U-value of 1.37 W/m^2 and a g-value of 0.3 could be chosen relatively freely within this range with little impact on energy use. For very small windows (window-to-floor ratios of 13% or less), increasing the g-value of this window to 0.6 would reduce total energy use. For larger windows, however, the lower heating demand due this change could not compensate for the larger cooling needs, and total energy use would increase.

For very well-insulated houses in the colder climates of Europe, the only investigation that could be found that considers the use of low g-values for shading purposes is the study by Vanhoutteghem and Svendsen (2014).

2.3 Need for new knowledge and research

This section identifies the gaps in knowledge that form the basis for each of the investigations included in this thesis and the related research questions.

2.3.1 Nearly zero-energy key parameters (P1)

This investigation was mainly needed method wise to establish a basis for studying the effect of roof and façade windows on energy, daylighting, and thermal comfort in nearly zero-energy houses.

The energy performance of windows in residential buildings has been studied using various approaches for modelling the building context they are part of. These range from highly simplified models where the whole house is modelled as one single zone, to models of a high level of complexity with regard to thermal zoning and the description of building systems, geometry and loads. Studies by Yohanis and Norton (2000), O'Brian, Athienitis and Kesik (2011), and Vanhoutteghem and Svendsen (2014) have shown that the use of appropriate thermal zoning is important when investigating the effect of windows on space heating and cooling demand (i.e. thermal comfort). These studies demonstrated that modelling a house as just one single zone tends to both underestimate space heating and cooling demands (i.e. overheating problems) and overestimate optimum window sizes. They argued that, at the very least, zones with and without direct solar exposure should be modelled separately. So what was needed in the present research was a set of properties that could bring the space-heating demand of a single-family house down to nearly-zero energy level without ignoring the differences between the zones. The windows need to be studied in a way that is transparent to the needs in spaces with different orientations. An approach was therefore needed where the windows can be studied in detail at room level, while the space-heating demand found in the individual rooms can be related to the space-heating demand of the overall house.

Since there has been very little research on very well-insulated houses that include variations on the window parameters individually, there could also be unexpected changes for example in the continuity of parameters due to the very low space-heating demand in nearly zero-energy houses. It was therefore found relevant to briefly address the following research question:

Q1: *Can the space-heating demand of nearly zero-energy houses be represented by a few key parameters?*

2.3.2 Parameter studies on façade windows (P2)

Few houses have roof windows but no façade windows. Any options for improving roof windows in a way that will meet energy, daylighting and thermal comfort needs must take façade windows into account. Existing research has indicated that the changed energy performance of windows in very well-insulated houses could make it easier than before to find façade window options with sufficient daylighting and thermal comfort with very small compromises in space-heating demand. For example:

- If the optimum window sizes for space-heating demand are smaller, they may correspond well with the window sizes needed for sufficient daylighting without overheating.
- If lower g-values can be used without considerable impact on space-heating demand, a balance between daylighting and thermal comfort would become easier to achieve.

This is part of the motivation for investigating the following research question:

Q2: *Can improvements in the energy performance of façade windows be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces?*

To answer this question, information about the following effects needs to be found and combined:

- The effect of various combinations of g-value, U-value and glazing size on space-heating demand and thermal comfort.
- The effect of various combinations of light transmittance and glazing size on daylighting.

For residential buildings, there have been a few studies that consider these effects at the same time. Foldbjerg and Asmussen (2013), Du, Hellström and Dubois (2013, 2014), Du (2014), Petersen (2015) and Carlucci et al. (2015) have studied the thermal performance of windows along with effects of the windows on daylighting or energy use for artificial lighting. However, these studies assumed either fixed size or fixed sets of properties for the windows investigated, so none of these studies made it possible to get a complete overview of the options with regard to sufficient daylighting and thermal comfort. More information is therefore needed to answer the research question Q2 above.

2.3.3 Parameter studies on roof windows (P3)

If options for improving façade windows can be found within a solution space defined by criteria for daylighting and thermal comfort, it is likely that improvements for roof windows can also be found within such a solution space. With regard to the options for improving the roof windows, the research question is the following:

Q3: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces?*

To answer this research question, the same effects as for the façade windows (Section 2.3.2) need to be studied.

For office buildings, Treado, Gillette and Kusuda (1984), Arasteh, Johnson, Selkowitz and Sullivan (1985), and Li, Lam and Cheung (2009) have studied the effect of skylights on energy use for heating, cooling and lighting combined. Targeted mainly on commercial buildings, other studies by Selkowitz and Gabel (1984), McCluney (1984a, 1984b), Arasteh, Johnson and Selkowitz (1985), and Beltran et al. (1994) have focused on the effect of skylights on daylighting or energy use for artificial lighting. Moreover, Acosta, Navarro, Sendra and Esquivias (2012), and Acosta, Navarro and Sendra (2013a, 2013b, 2015) have studied the daylighting performance of a series of skylight technologies, such as lightscoop, monitor, and lightwell skylights.

For residential buildings, the effect of roof windows on daylighting has been studied by Dubois et al. (2003), Johnsen, Dubois and Grau (2006), Mardaljevic (2008), and Mardaljevic et al. (2012). However, very few studies on roof windows for residential use could be found that consider the thermal performance of the windows and their effect on daylighting or energy use for artificial lighting at the same time. For a lightly insulated loft room in the UK, Robertson and Thompson (2006) studied the optimum size of sloped roof windows in this way and found slightly larger window sizes for optimum energy use than for daylighting. For well-insulated residential buildings, studies by Foldbjerg and Asmussen (2013), Du, Hellström and Dubois (2013, 2014), Du (2014), and Carlucci et al. (2015) include information about the thermal performance of roof windows and their effect on daylighting or energy use for artificial lighting at the same time. However, since these studies consider either fixed size or fixed sets of properties for the roof windows investigated, they do not provide sufficient information on energy, daylighting and thermal comfort with various parameters to answer the research question Q3 above.

2.3.4 Permanent vs. dynamic solar shading (P4)

Both permanent and dynamic shading solutions have clear advantages. A permanent solution, such as solar-control coating, is cheaper than dynamic shading, for example, and would not face the same operational challenges or depend on successful control to perform well. Dynamic shading, on the other hand, may be highly valued by users and designers who appreciate architectural freedom and flexibility in controlling the indoor environment. An informed decision about one or the other shading strategy, however, requires that users know what they can expect to achieve in terms of energy, daylighting and thermal comfort with each option.

In lightly insulated houses, increasing the window area facing south usually reduces space-heating demand. In this way, the use of large south-oriented windows has been associated with improvements in both daylighting and space-heating demand. These two benefits then became arguments for why dynamic solar shading should be used to prevent overheating instead of reducing the glazing size. Moreover, although the g-value of the windows could have been reduced considerably with no impact on daylighting (as long as the light transmittance was kept the same), high g-values were generally considered significant for achieving a low space-heating demand. For these reasons, it may have seemed that there was no need to quantify the potentials on energy, daylighting and thermal comfort with dynamic and permanent shading strategies in further detail before concluding that dynamic solar shading would be the most beneficial. In very well-insulated houses, however, the effect of both window size and high g-values on space-heating demand was found in the literature review to be less obvious. Similarly, the potential effects of using dynamic shading on space-heating demand are less obvious. This yields the following sub-hypothesis:

SH4: *Dynamic solar shading can make room for more daylighting without overheating, but cannot reduce energy use for space heating.*

If this hypothesis is true, the use of dynamic shading will not change the conclusions with regard to the useful options for improving roof windows.

To test this hypothesis in a way that takes into account the full potential of using either shading strategy (see Section 5.4), the performance of the options that can be found within the solution space for daylighting and thermal comfort with each shading strategy needs to be mapped and compared. This requires information about the same effects of various parameters on energy, daylighting and thermal comfort as stated in Section 2.3.2. Moreover, daylighting has to be handled dynamically in order to take the effect of the shading on daylighting into account in the comparisons.

For office buildings, Johnson et al. (1984), Sullivan et al. (1996), E. S. Lee, DiBartolomeo and Selkowitz (1998), Gugliermetti and Bisegna (2003), E. S. Lee and Tavil (2007), Poirazis, Blomsterberg and Wall (2008), Motuziene and Juodis (2010), David et al. (2011), M. V. Nielsen, Svendsen and Jensen (2011), Appelfeld, McNeil and Svendsen (2012), Tzempelikos and Shen (2013), Grynning, Time and Matusiak (2014), Huang, Niu and Chung (2014), Goia and Cascone (2014), Yun, Yoon and Kim (2014), Freewan (2014), Atzeri, Cappelletti and Gasparella (2014), Singh, Lazarus and Kishore (2015), and Shen et al. (2015) have studied the thermal performance of dynamic solar shading together with effects on daylighting or electricity use for artificial lighting.

For residential buildings, Sullivan et al. (1995), Karlsson, Karlsson and Roos (2000), Apte, Arasteh and Huang (2003), Gugliermetti and Bisegna (2007), Arasteh et al. (2007), O'Brian, Athienitis and Kesik (2011), Tsikaloudaki et al. (2012), Tsikaloudaki et al. (2015), Kim et al. (2012), Ali Ahmed (2012), Mavrogianni et al. (2014), Vanhoutteghem and Svendsen (2014), and Firląg et al. (2015) have studied mainly the thermal performance of solar shading. With regard to dynamic roof windows, Klems (2001) examined the summer performance of an electrochromic skylight through measurements in a test chamber, and concluded that some 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, Yao and Zhu (2012), Foldbjerg and Asmussen (2013), Du, Hellström and Dubois (2013, 2014), Du (2014), Petersen (2015), Carlucci et al. (2015), and DeForest et al. (2015) have studied the thermal performance of solar shading and the effect of the shading on daylighting, visual comfort or electricity use for lighting at the same time. However, since these studies assumed either fixed size or fixed properties of the glazing options compared, the full potential of using one or the other shading strategy was not transparently addressed. More information is therefore needed to answer the following research question:

Q4: *Can dynamic solar shading make room for more daylighting without overheating? Can dynamic solar shading reduce energy use for space heating?*

2.3.5 Performance in complete houses (P5)

In the first part of this research, options for improving the roof windows were identified by studying the effect of various parameters at room level. The energy use at room level was then linked to the energy use at building level by considering houses with simplified floor plans made up from the rooms studied. In real houses, however, the floor area is distributed differently, and rooms may contain windows with more than one type of slope and orientation. Information is therefore needed about the extent to which the effect of the window parameters on space heating found at room level will hold true in houses with more typical floor plans. The research question is:

Q5: *Does the relative importance of roof-window parameters found at room level hold true at building level?*

Information about economic benefits and the scope for investment in improved roof windows is central for whether improved products can be realised and made commonly available to the user. However, with the large insulation thicknesses needed in the building envelope to reduce energy consumption to nearly zero, the cost of compensating for building components that are not optimised for a minimum energy use by using more insulation has increased significantly. This means that it might be possible to make improved roof windows available for prices that are less than the prices that are currently being paid to meet nearly zero-energy requirements by means of insulation. If improved roof windows can be made available at prices within such scopes for investment, this would provide building owners with a more cost-optimal choice of basic building components. The research question is:

Q6: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels make it possible to build nearly zero-energy houses in a more cost-effective way?*

For façade windows, Jaber and Ajib (2011) and Karabay and Arıcı (2012) have examined the cost-optimal selection of glazing using common economic evaluation techniques requiring cost estimation inputs. As part of a study by Hansen and Vanhoutteghem (2012) on the economic optimisation of new low-energy homes, the cost-effectiveness of existing windows has also been evaluated in relation to other building components. For roof windows, however, very few studies could be found that consider their performance in very well-insulated homes. Foldbjerg and Asmussen (2013), Du, Hellström and Dubois (2013, 2014), and Du (2014) have studied the effect of existing roof windows on energy, daylighting and thermal comfort in well-insulated residential buildings, but none of these studies looked into the economic effect of improving the current best standard-practice roof windows. More information is therefore needed to answer the research question Q6 above.

Chapter 3

Methods

This is meant as a look-up chapter providing information about central parts of the method used throughout this research. The chapter introduces the performance parameters and criteria used for the evaluation of energy, daylighting and thermal comfort, the glazing diagram used in Papers 2–4 to map and compare options with sufficient daylighting and thermal comfort, the method used in Paper 5 to determine the scope for investment in improved roof windows in typical houses, and the simulation tools with relevant assumptions.

3.1 Performance parameters and criteria

Mechanical cooling is not common in Danish homes, and electricity consumption for artificial lighting is not included in the requirement for acceptable energy use. So for residential buildings in Denmark, the main variable defining energy usage is the space-heating demand (Section 3.1.1), while daylighting and thermal comfort are considered separate performance parameters that are evaluated on the basis of their own criteria (Sections 3.1.2–3.1.3).

3.1.1 Space-heating demand

Danish building regulations specify a fixed criterion for maximum energy usage in nearly zero-energy residential buildings, which new houses of any size will have to comply with from 2020. According to this requirement, the annual primary energy usage, covering space heating, cooling, domestic hot water, and electricity for pumps and ventilation fans should not exceed 20 kWh per m^2 gross floor area. This is the energy usage after the energy demands in the houses have been multiplied by the primary energy factors of 0.6 for district heating and 1.8 for electricity. Assuming that 5 kWh/m^2 of primary energy will be needed for electricity, 15 kWh/m^2 are left for space heating and domestic hot water. This corresponds to a maximum heating demand (or end energy use for heating) of 25 kWh/m^2, of which domestic hot water will take up a fixed amount of 13 kWh/m^2 by definition. This leaves an energy demand of **12 kWh/m^2** for space heating (and/or cooling).

This is the criterion for maximum space-heating demand used as a basis in all investigations (except for the first one). This criterion is also used in Rome. However, different versions of the criterion are used depending on whether the target of the investigation is a whole house, a section of a house, or a specific room. This is further specified in the overview in Chapter 4 and in the presentation of each of the investigations in Chapter 5.

3.1.2 Daylighting

The establishment of reasonable criteria for daylighting is an issue that is under continuous debate, supported by research on the effects of daylighting on human health (Webb, 2006), and Danish legislation defines sufficient daylighting in homes only in vague terms.

In this research, two different criteria for minimum daylighting were used. With ‘floor space area’ referring to measuring positions evenly distributed over a horizontal plane 0.85 m above floor level, these are:

1. A climate-based criterion, where at least 75% of the floor space area should receive illuminances of min. 300 lx for 50% of the daylight hours (Spatial coverage of DA 50% $\geq$ 75%).
2. A climate-dependent criterion, where at least 50% of the floor space area should meet a certain target daylight factor (DF_{target}) specific to the location (Median DF $\geq DF_{target}$).

The first criterion was established in view of the recommendations of the Illuminating Engineering Society for Spatial Daylight Autonomies in offices (IES, 2013). This criterion is fully climate-based (Mardaljevic, 2006) and is the main criterion used throughout this research to ensure windows designed for comparable daylighting across climate and orientation. The second criterion refers to an approach suggested by Mardaljevic and Christoffersen (2013, 2017) that relates daylight factors to the diffuse daylight access at a location based on the weather data for this location. If the daylight factor suggested for the given climate (DF_{target}) is met, this would usually ensure an access to diffuse daylighting of at least 300 lx for 50% of the daylight hours. In some of the investigations, this criterion was used alone, as a simplification. Elsewhere, it was used together with the climate-based criterion to ensure that daylighting in the rooms receiving the most direct sun would also meet some minimum standards under overcast conditions. This is further specified in Chapters 4 and 5. Glare was not studied specifically. It was assumed that occupants can use internal screens or curtains to avoid glare if needed.

3.1.3 Thermal comfort

Two different criteria for acceptable thermal comfort were used throughout the investigations:

- Max. 100 h per year with operative temperatures (T_o) above 26°C (referred to as 'Max. 100 h > 26°C').
- Max. 100 h per year with T_o exceeding the comfort limit as defined in accordance with the Adaptive Thermal Comfort (ATC) model (referred to as 'Max. 100 h > ATC Limit').

The first is the criterion previously used in Denmark for the evaluation of thermal comfort in residential buildings (BR, 2014), while the latter is based on Class II of the ATC model in EN 15251 (CEN, 2007). Given that occupants are free to use windows for venting, adjust their clothing, and adapt to indoor conditions in other ways, the ATC model states that the comfortable operative temperature is a function of the running mean outdoor air temperature at the location. The upper limit for thermal comfort is therefore not a fixed temperature, but a variable temperature that depends on recent temperatures outdoors. In Denmark, the criterion of max. 100 h per year exceeding the ATC Limit corresponds well with the recently updated comfort criterion for homes in the Danish Building Code of max. 100 h above 27°C (BR, 2016 and Petersen, 2015). In Rome, comparisons made throughout this PhD study showed that 100 h exceeding the ATC Limit corresponds to about 500 h above 28°C, 800 h above 27°C and 1300 h above 26°C.

Temperatures exceeding the comfort limit of 26°C or as defined by the ATC model are sometimes referred to as 'excessive temperatures', whereas the term 'overheating' refers to the situation where the criterion of max. 100 h with excessive temperatures is not met.

3.2 The glazing diagram for visualising the useful options

The glazing diagram was developed as a tool to map and compare the effect of various glazing options with sufficient daylighting and thermal comfort. The diagram consists of three layers: one for space-heating demand, one for thermal comfort, and one for daylighting. When these three layers are plotted on top of each other, the effect of various combinations of glazing g-value and glazing-to-floor ratio on space-heating demand can be studied within a solution space defined by criteria for daylighting and thermal comfort. This is explained in the reader's guide to the glazing diagram in Figure 3.2.1. Further explanation is given along with the results (Chapter 5), including two examples of how the solution space can be used (shown in Section 5.2). More information can also be found in Papers 2–4. It should be noted that the first vertical line from the left always refers to the glazing size needed for minimum daylighting with a light transmittance of 70%.

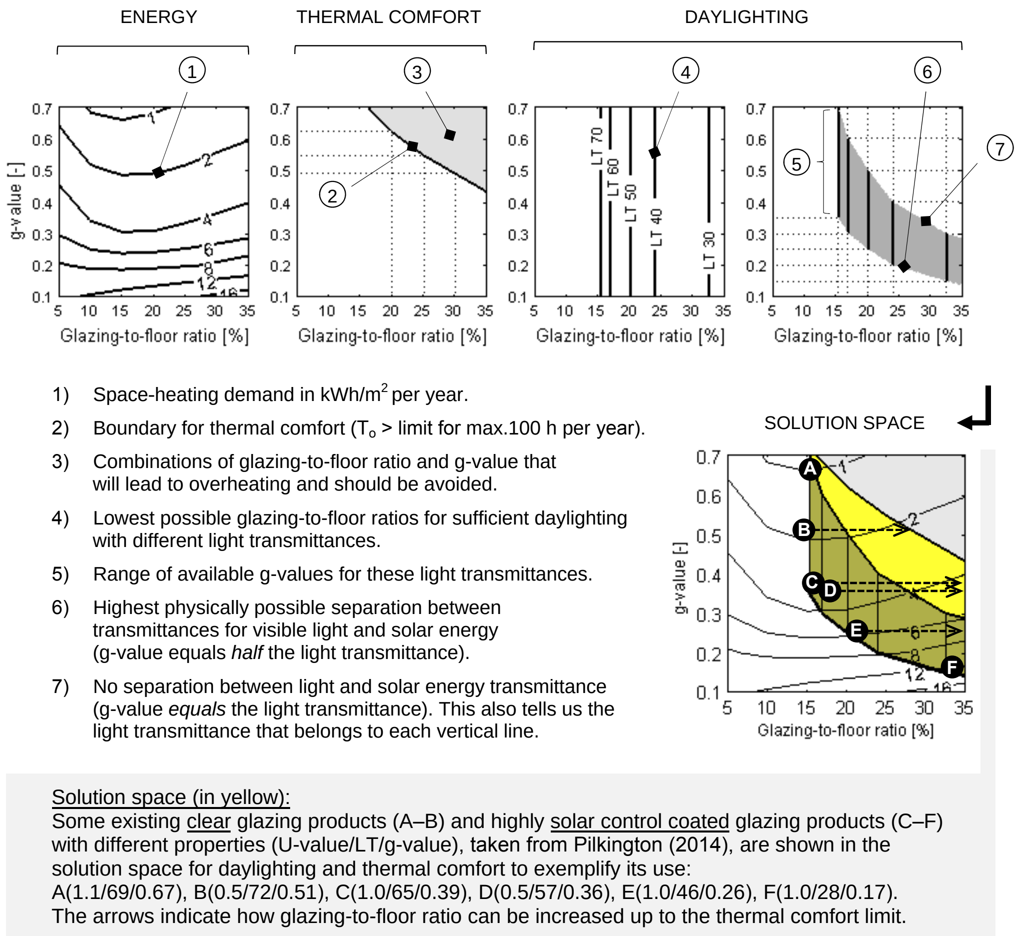


Figure 3.2.1. *Reader's guide to the glazing diagram.*

3.3 Method for determining the scope for investment

This section presents the method used in the investigation described in Paper 5 to determine the scope for investment in improved roof windows.

Any attempt to determine the cost effectiveness of roof windows improved to levels beyond current best-standard practice by means of common economic evaluation techniques (Meier, 1983a,b) would require qualified cost estimations for products that do not yet exist or are not yet commonly available. Such techniques would be of little use in this case. Instead, to answer the research question Q6, a different approach was used, in which the scope for investment in the improved roof windows was quantified.

The Danish Building Code (BR, 2016) has already defined a fixed requirement for the maximum energy use permitted in nearly zero-energy residential buildings, and from 2020 all new houses will have to comply with this requirement in one way or another. This makes it possible to establish a measure of the scope for investment in improved roof windows by comparing the energy-saving potential of various types of roof window improvement with the cost of saving that energy by current means. Given that a building has the best high-end practice façade windows currently available and that all other building components that affect space-heating demand have been optimised to nearly ideal levels, the amount of insulation inserted in the building envelope is the parameter that would probably be used to compensate for the performance of the roof windows. The scope for investment in improved roof windows was therefore determined on the basis of the cost of the insulation that would not be needed in the building envelope to comply with the energy requirement if the improved roof windows were installed instead of the roof-window options that are current best standard-practice.

It will be up to the manufacturers to determine the prices at which the improved roof windows can be made available. However, provided the improvements (including the replacements needed within a time frame corresponding to the lifetime of the insulation saved) can be made available at prices that are within the scope for investment identified, future energy requirements can be met in a cheaper and more cost-effective way.

The average cost I_{ins} per surface area of increasing the insulation thickness in walls, roof or ground floor by 1 cm was estimated as EUR 1.613/(cm m^2) excluding VAT, based on the prices used by the Danish Building Research Institute in a study of cost-optimal energy use in homes (Aggerholm, 2013). Two ways of determining the scope for investment are given below.

3.3.1 Simplified estimation for small improvements

The scope for investing in a roof window improvement with small impact on the space-heating demand can be estimated with reasonable accuracy by multiplying the energy saved in the house by installing the improvement ΔE_{win} by the cost of using more insulation to save 1 kWh/m^2. The insulation costs saved in EUR per m^2 improved roof window A_{win} would then be:

$$\textit{Saved insulation costs} \ = \left(\Delta E_{win} \cdot \frac{I_{ins} \cdot A_{ins}}{\Delta E_{ins}} \right) / A_{win} \tag{3.1}$$

where ΔE_{ins} is the energy saved at building level by increasing the insulation thickness in all constructions by 1 cm for the house with the standard-practice roof windows and A_{ins} is the surface area of the constructions in the house after subtraction of roof and façade window area.

3.3.2 Direct calculation from the insulation not needed

The scope for investment in any improvement can be determined directly from the difference in cost between the insulation needed before and after installing the improvement, as found through simulation. The insulation costs saved in EUR per m^2 improved roof window would then be:

$$\textit{Saved insulation costs} \ = \frac{(V_{ins\ ref} - V_{ins\ impr}) \cdot I_{ins} \cdot 100}{A_{win}} \tag{3.2}$$

where $V_{ins\ ref}$ is the volume of the insulation needed in the house with the standard-practice roof windows and $V_{ins\ impr}$ is the volume of the insulation needed in the house with the improved roof windows.

3.3.3 Considerations on the differences in lifetime

The lifetime of the roof window is part of the development of a competitive product and may also differ for the various components of the window, so for transparency, the scope for investment is presented directly as the savings in insulation costs defined above, with no corrections for differences in lifetime between window and insulation. So, the scope for investment will have to cover any necessary replacements of glazing and/or window as a whole in a time frame corresponding to the lifetime of the insulation. Assuming that the lifetime of the building envelope is 40–60 years (Aggerholm, 2013), the lifetime of the insulation and the window construction could be fairly similar, whereas the sealed glazing units may have to be replaced 1–2 times. The scope for investment (i.e. savings in insulation costs) identified may therefore have to be divided by 2 or even 3 to find the competitive price of the improvement per area final window product.

3.4 Simulation tools

The thermal simulations and the simulations of daylighting were carried out using separate tools. In both types of simulation, weather data from the Danish Reference Year (Jensen and Lund, 1995) were used for Copenhagen and weather data from EnergyPlus's homepage (EnergyPlus, 2013) were used for Rome and Bratislava. Matlab was used for post-processing of simulation outputs.

3.4.1 Thermal simulations with EnergyPlus and jEPlus

Space-heating demand and operative temperatures in Papers 2–5 were simulated using EnergyPlus Version 8-4-0 (U.S. Department of Energy, 2016) in combination with the tool jEPlus (Zhang, 2009, and Zhang and Korolija, 2010) for automated parametric analysis. With regard to these simulations, it should be noted that glazing and frame properties were modelled using the simple glazing material method (Arasteh, Kohler and Griffith, 2009), which allows the windows to be represented by simple performance indices. No air or heat exchange between zones was taken into account.

In Paper 1, another tool, WinDesign, was used for the thermal simulations, which is further described in the paper.

3.4.2 Daylighting simulations with DAYSIM

Daylighting was simulated using the RADIANCE-based daylighting analysis tool, DAYSIM (DAYSIM, 2016). The daylight simulations in Papers 3–5 were carried out using DDS mode, which means they can be repeated for multiple climates without needing to repeat the heaviest part of the simulation.

Chapter 4

Overview of set-up and assumptions

Table 4.1 provides an overview of the set-up and assumptions for the five investigations carried out to test sub-hypotheses SH1–SH6. The overall methodology related to each of the investigations is given along with the results presented in Chapter 5, and additional modelling assumptions can be found in the papers. The investigations all revolve around the basic assumptions described in Paper 1 (see Table 4.3), but vary in the window characteristics studied, the insulation levels, the performance criteria, etc.

Table 4.4 summarises the partial findings from Papers 2–3 with regard to glazing sizes of roof and façade windows for the minimum daylighting and the solar-control coating needed to avoid overheating in rooms with a reasonable layout for daylighting. These findings were used to set up the two houses in Paper 5 for sufficient daylighting and thermal comfort in all parts. This was done by first dividing each room or thermal zone into 'daylit spaces' (i.e. spaces which can reasonably be served by windows with one type of slope and orientation). Then, the information in Table 4.4 was used to select windows with the right size and g-value. Finally, daylighting and thermal comfort were tested using simulation, and the glazing sizes were adjusted for daylighting where needed. Comparison of the final glazing-to-floor ratios with those suggested in Table 4.4 shows differences of at most 2% for all window types, except for the sloped roof windows in Case A. For these windows the final ratios were about 4–6% larger. Moreover, the thermal comfort criteria were met in all zones. This procedure is documented in detail in Paper 5.

No external obstructions were taken into account in the daylight simulations, and the surface reflectance was 70% for walls and ceilings, and 30% for floors. The thicknesses of both roof and walls were 0.45–0.5 m, except in Paper 1 where they varied realistically with the insulation thicknesses, and in Paper 5 where the roof thicknesses were set to 0.7 m.

Table 4.1. *Overview of the five investigations used to test the sub-hypotheses.*

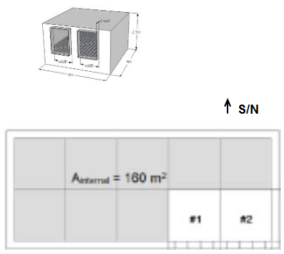
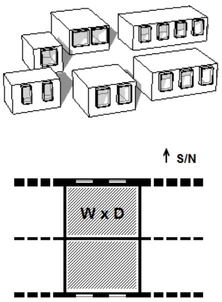
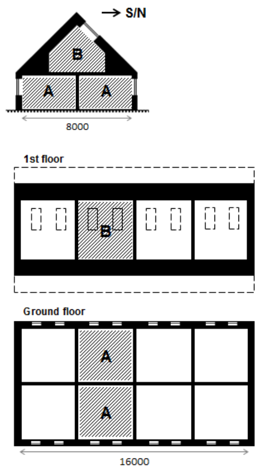
Investigation	Nearly zero-energy key parameters	Parameter studies on façade windows	Parameter studies on roof windows
Paper	1	2	3
Sub-hypothesis	SH1	SH2	SH3 (+ SH2 + SH5)
Focus	*Approach for modelling the nearly zero-energy context.* *Test continuity of parameters.*	*Solution space in rooms with various geometries.* *Effect of parameters*	*Solution space in rooms with a reasonable layout.* *Possibilities for improvement.*
Climate	Copenhagen, Rome, Bratislava	Copenhagen	Copenhagen, Rome
			
Geometry	<u>Rooms</u> of 4 x 4 m in the middle section and corners of a 1-storey house of 160 m^2 with symmetrical floor plan.	<u>Rooms</u> of various shapes (Table 5.2.1) in the middle section of a 1-storey house.	<u>Rooms</u> of 4 x 4 m in the middle section of a 1½-storey house of about 200 m^2 with simplified floor plan.
Window type and orientation	Façade windows 90° N, 90° S	Façade windows 90° N, 90° S	Façade and sloped roof windows 90° N, 90° S, 45° N, 45° S
Window characteristics studied	g-value: 0–0.7 U_g: 0–5 W/m^2K LT (i.e. size): 50–70%	Glazing diagram (Table 4.2) U_g: 0.3, 0.5, 0.7, 0.9.	Glazing diagram (Table 4.2) U_g: 0.3, 0.5, 0.7, 0.9 (Copenhagen) U_g: 0.7, 0.9, 1.1, 1.3 (Rome) Combined with the frame constructions in Table 5.3.1.
Energy target	Max. space-heating and cooling demand of the <u>house</u>: **13** kWh/m^2	Max. space-heating demand of the building <u>section</u>: **<12** kWh/m^2 (depends on geometry)	Max. space-heating demand of the building <u>section</u>: **10** kWh/m^2
Daylight criterion	Median DF ≥ DF_{target}	Median DF ≥ 2.1%	Spatial coverage of DA 50% ≥ 75%
Comfort criterion	Evaluated via the energy use for cooling	Max. 100 h > 26°C	Max. 100 h > ATC Limit
Max. venting rate	3 h^{-1} (all)	3 h^{-1}	3 h^{-1} (Copenhagen) 4 h^{-1} (Rome)
Insulation level, U_{wall} | U_{roof} | U_{floor} (W/m^2 K)	0.12 | 0.07 | 0.06 (Copenhagen) 0.20 | 0.14 | 0.11 (Rome) 0.10 | 0.06 | 0.05 (Bratislava)	0.10 | 0.08 | 0.09	0.13 | 0.08 | 0.10 (Copehagen) 0.28 | 0.15 | 0.10 (Rome)
Other settings	Table 4.3, but no infiltration.	Table 4.3	Table 4.3

Table 4.1. Overview of the five investigations – continued.

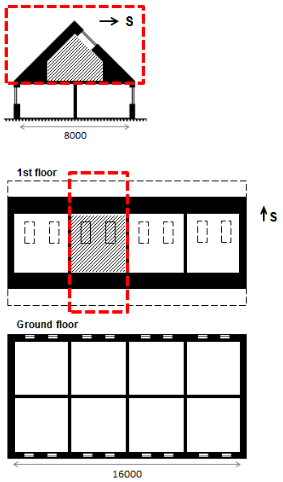
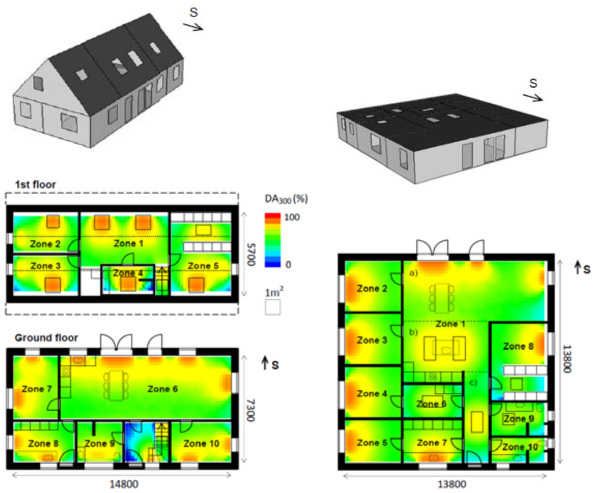
Permanent vs. dynamic solar shading	Performance in complete houses
4	5
SH4	SH5 + SH6 (+ SH1)
Comparison of potential achievements in energy, daylighting and thermal comfort with and without dynamic shading.	*Effect of changes in the current best standard-practice roof windows in typical houses as a function of insulation level.* *Scope for investment in specific examples of improved roof windows.*
Copenhagen, Rome	Copenhagen
 	
Loft room of 4 x 4 m in the section of the 1½-storey house studied in Paper 3.	Two single-family houses with typical floor plans (both 213 m^2): • Case A – 1 ½-storey house with *sloped* roof windows • Case B – 1-storey house with *horizontal* roof windows
Sloped roof windows 45° S	Sloped and horizontal roof windows (+ fixed façade windows) 45° N, 45° S, 0° (+ 90° N, 90° S, 90° E, 90° W)
Glazing diagram (Table 4.2) with and without dynamic shading. Studied for the thermal properties of glazing and frame in Table 5.4.1.	Variations in the current best standard-practice roof windows used as a reference (see Section 5.5.1 and Tables 5.5.2–5.5.3): • U_g +/-0.1, g-value +/- 0.1, and LT +/- 10% (i.e. -/+ size) • Specific roof-window improvements: #A–E
Max. space-heating demand of the loft room: **16** kWh/m^2	Max. space-heating demand of the houses: **12** kWh/m^2 for 2020-level (i.e. 'nearly zero-energy' consumption) 22 kWh/m^2 for 2015-level 40 kWh/m^2 for 2010-level
Spatial coverage of DA 50% ≥ 75% Improvements quantified in terms of time.	Spatial coverage of DA 50% ≥ 75% Median DF ≥ 2.1%
Max. 100 h > ATC Limit Improvements quantified in terms of time.	Max. 100 h > ATC Limit Time with T_o > 26°C and effect of larger air-change rates indicated.
3 h^{-1} (Copenhagen) 4 h^{-1} (Rome)	3 h^{-1}, 6 h^{-1} and 9 h^{-1}
0.13* | **0.08** | 0.10* (Copenhagen) 0.28* | **0.15** | 0.10* (Rome) *) Relevant only for the energy target	Varying levels always complying with the three energy targets above. To consume nearly zero-energy with the reference windows (REF): 0.14 | 0.10 | 0.10 (Case A) and 0.10 | 0.07 | 0.07 (Case B)
Table 4.3	Table 4.3, but with realistic linear heat losses inserted at room level.

Table 4.2. *Variables included in the glazing diagram (Section 3.2).*

Glazing-to-floor ratios[1)] (%)	5 10 15 20 25 30 35
Glazing g-value (–)	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

1) The ratios refer to internal floor area. Some ratios were not relevant in all cases. Daylighting was modelled for ratios up to 40% in increments of 2.5%.
2) Not relevant for facade windows. Also modelled as diffuse transmittance for the sloped roof windows in Paper 4 to find the illuminances with shading.

Table 4.3. *Settings for system properties and internal loads.*

Heating set point (°C)	20
Venting set point (°C)	23
Infiltration rate (h^{-1})	0.05
Mechanical ventilation rate (h^{-1})	0.6
Efficiency of heat recovery (–)	0.9
Internal loads from people, equipment and lighting (W/m^2)	5

Table 4.4. *Minimum glazing-to-floor ratios for daylighting and solar-control coating needed to avoid overheating in rooms[1)] with a reasonable layout for daylighting in the climate of Copenhagen. Minimum daylighting is defined as 300 lx in 75% of the floor space area for 50% of the daylight hours, and in brackets are the ratios needed to meet a median DF of 2.1%.*

Orientation	South		Horizontal		North
Slope	90°	45°	00°	45°	90°
					
LT 70%	15.6 (17.8)	9.7 (8.5)	10.0 (6.6)	13.2 (8.5)	21.3 (17.8)
LT 60%	17.4 (20.2)	11.0 (9.6)	11.5 (7.5)	15.1 (9.6)	24.5 (20.2)
LT 50%	20.7 (23.7)	12.7 (11.2)	13.2 (8.7)	17.9 (11.2)	29.5 (23.7)
LT 40%	25.0 (30.1)	15.0 (13.6)	16.0 (10.5)	21.4 (13.6)	36.4 (30.1)
LT 30%	34.1 (43.0)	19.2 (17.6)	20.8 (13.2)	27.9 (17.6)	– (43.0)
LT 20%		27.8 (25.4)	31.4 (19.0)	40.2 (25.4)	
LT 10%		45.2 (42.0)	54.5 (38.6)	– (42.0)	
Solar-control coating [2)]	Moderate/ Close to ideal	Close to ideal	Close to ideal	Not needed	Not needed

1) Rooms of 4 x 4 m with a glazing head-height of 2.4 m for façade windows and roof and wall thicknesses of 0.45 m.
2) Close-to-ideal solar-control coating means that the g-value equals nearly half of the light transmittance (LT).

Chapter 5

Results of the investigations

The following sections present the main findings of the five investigations described in Papers 1–5 one by one along with relevant methodology.

5.1 Nearly zero-energy key parameters (P1)

This section presents results from the investigation described in Paper 1 (P1), "*Investigation and description of European buildings that may be representative for 'nearly zero' energy single-family houses in 2020*".

These form the basis for later investigations and are also related to the research question Q1: *Can the space-heating demand of nearly zero-energy houses be represented by a few key parameters?*

To make it possible to study the usefulness of various options for improving the windows in nearly zero-energy houses, a set of key parameters and properties is needed that can adequately represent this type of building. Furthermore, this set needs to be defined in a way that makes it possible to study the effect of the windows on energy, daylighting and thermal comfort in detail in rooms with different orientations, while the energy use found at room level can be related to the energy consumption of the overall house.

Based on reasoning and the simulation of daylighting and energy use for space heating and cooling, Paper 1 provides such a set of properties that enables a one-storey single-family house to consume nearly zero energy when located in Rome (Italy), Bratislava (Slovakia) and Copenhagen (Denmark). The maximum total energy use for space heating and cooling was set at **13** kWh/m^2 in accordance with Danish definitions of nearly zero-energy consumption (see Section 3.1.1), and the houses were designed for sufficient daylighting in accordance with the climate-dependent criterion described in Section 3.1.2. With this criterion, a target daylight factor specific to the location (DF_{target}) should be met in at least half of the floor space area.

5.1.1 Defining the set of key parameters

Consider a one-storey single-family house consisting of ten quadratic room units with inner dimensions of 4 x 4 x 2.5 m and oriented north-south. This resulted in a simple symmetrical floor plan of 160 m^2 in total (Figure 5.1.1), which leaves the two orientations equally important and ensures a reasonable room depth for daylighting in both sides of the house. With this layout, the north- and south-oriented parts of the building are comparable, and the whole house can be studied on the basis of simulations of only two types of rooms:

- Type #1 with only one façade exposed to the outside climate, which is the worst case for thermal comfort and utilisation of solar gains.
- Type #2 at the building corners with significantly larger heat losses.

The energy use of the overall house would be the area-weighted average of the energy use in these two room types oriented north and south.

It was then assumed that all parameters affecting the space-heating demand of the house, except for parameters related to the windows and insulation in walls, roof and floor, were already optimised to nearly ideal levels. An air-tight building envelope with construction details of very high quality kept infiltration and linear heat losses to a minimum, while mechanical ventilation with a heat recovery efficiency of 90% and a bypass during the cooling season was used to ensure a fresh-air supply of 0.6 h^{-1} all year round with minimal heat losses. Furthermore, the thermal capacity for all rooms was set to 260,000 J/K m^2, and we assumed a constant heat load from people and equipment in each room of 5 W/m^2 in total. The heating and cooling set-points were 20°C and 26°C respectively, and it was assumed that a venting rate of up to 3 h^{-1} could be achieved by opening the windows in the rooms when indoor temperatures exceeded 23°C.

This left the variables that define the final space heating and cooling demand of the house: the insulation thicknesses in walls, roof and floor, and the size and properties of the windows (see Table 5.1.1).

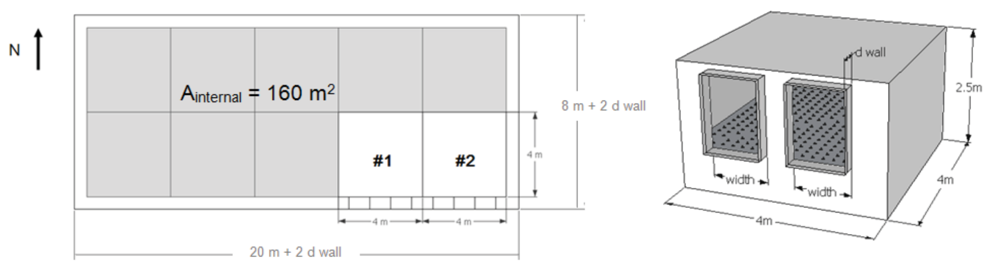
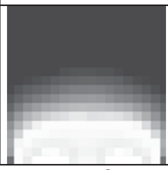
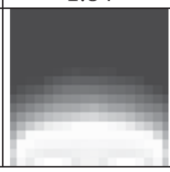


Figure 5.1.1. *Floor plan of the one-storey house composed of the 10 room units.*

Table 5.1.1. *Example of the values selected for the building's variable parameters, which led to sufficient daylighting and nearly zero-energy consumption.*

Variable parameters		Unit	Rome	Bratislava	Copenhagen
Insulation*	Insulation thickness	mm	125	300	250
	Wall thickness	m	0.325	0.500	0.450
	U-value, wall	W/m^2 K	0.20	0.10	0.12
	U-value, roof/floor	W/m^2 K	0.14/ 0.11	0.06/ 0.05	0.07/ 0.06
Window size	Fraction of internal floor area	%	24	30	32
Glazing	Type	-	2-layer	3-layer	3-layer
	U-value	W/m^2 K	1.0	0.5	0.5
	g-value	-	0.27	0.27	0.27
	LT	%	50	50	50
Daylighting with the final solution	DF_{target}	%	1.56	1.84	2.11
	Spatial distribution of the targeted DF. In the darkest areas $DF < DF_{target}$				

*) Additional properties of the building envelope; U_{frame} = 1.34 W/m^2 K (width = 0.057 m, psi = 0.33 W/m K), psi $_{win/wall}$ = 0.01 W/m K, and psi $_{foundation}$ = 0.13 W/m K. Insulation in roof/floor is double the amount in walls.

Reasonable values for the variable parameters were found by iterating between window size, light transmittance (LT) and wall depth for sufficient daylighting and acceptable choices of insulation thicknesses and window properties (U-value and g-value) for total energy use. The final choice of solution is shown in Table 5.1.1 along with documentation on the fulfilment of the daylight criterion.

Figure 5.1.2 shows the final space heating and cooling demands with the set of properties defined separately for the north- and south-oriented parts of the building and for the house as a whole.

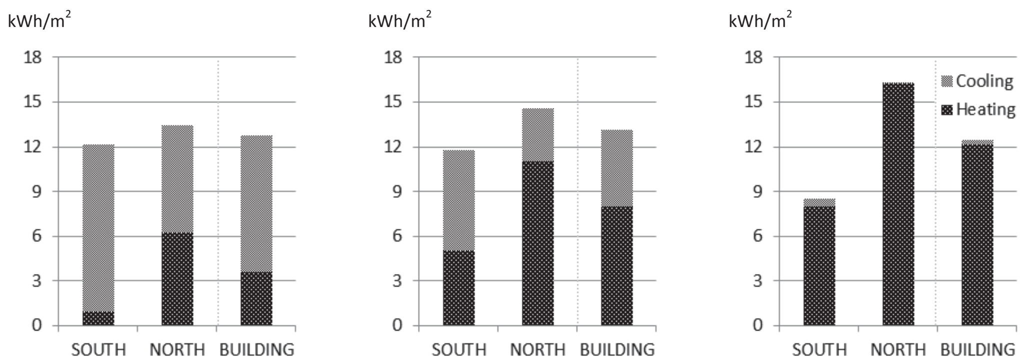


Figure 5.1.2. *Space-heating and cooling demands with the set of properties defined in Rome, Bratislava and Copenhagen (from left to right).*

5.1.2 Example of variations in glazing properties

Figures 5.1.3–5.1.5 show examples of variations in glazing g-value, U-value and LT (i.e. glazing size) for the parts of the building oriented north and south, when the set of properties defined above is used as reference. Variations could also have been shown for one of the two room types individually, which would for example be more useful for the evaluation of thermal comfort as a separate parameter (as in the other investigations).

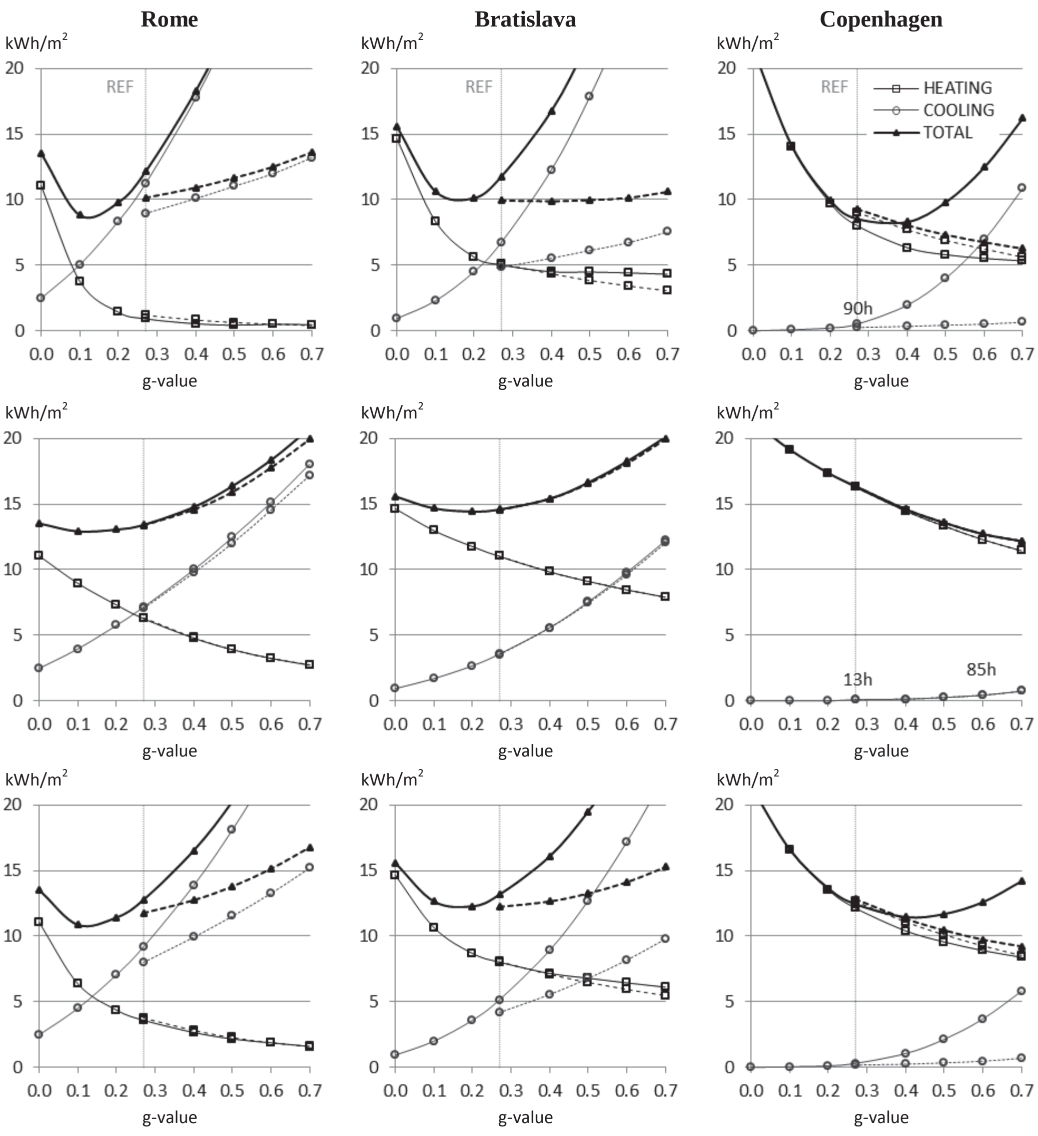


***Figure 5.1.3**. Variations in the g-value for south-oriented glazing (top row), north-oriented glazing (middle row), and glazing in the house as a whole (bottom row). The dashed lines show the results when using dynamic solar shading with a shading factor of 0.2 activated at set-point for solar irradiation of 300 W/m^2.*

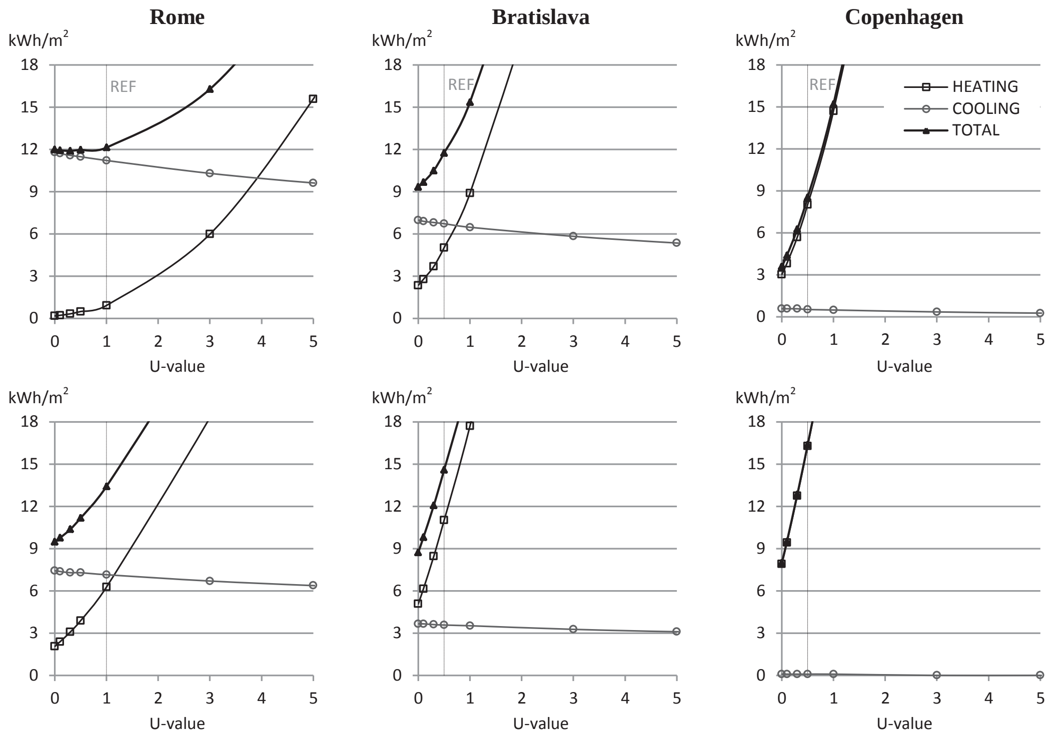


Figure 5.1.4*. Variations in the U-value for glazing oriented south (top row) and north (bottom row).*

One thing to note is that the space-heating and cooling demands change continuously with the variations in parameters. Moreover, the effect of some parameters differs significantly between the two parts of the building.

The variations in g-value (Figure 5.1.3) show how the space-heating demand in north-oriented rooms decreases almost linearly with increased g-value. In contrast, the effect of the g-value in south-oriented rooms is not linear and tends to diminish at rather low g-values. The figure shows that the solar gains due to the g-value of 0.28 were responsible for savings in space-heating demand of about 10–15 kWh/m^2 (depending on climate) compared to a situation with no solar gains at all. However, when the g-value is more than about **0.2–0.3** in Rome and Bratislava or **0.4–0.5** in Copenhagen, the further reductions in space heating were only 1–2 kWh/m^2. At g-values slightly lower than these values, rather clear optimum g-values for total energy use (when space heating and cooling are considered equally important) can be observed in all climates. For the climate of Copenhagen, for example, the optimum g-value for total energy use is smaller in the south-oriented part of the building than for the house as a whole, which clearly shows that important information could have been lost by not treating the two parts of the building separately.

The savings in space-heating demand from increasing the g-value from the reference of 0.28 to more than 0.7 in the two parts of the building would be:

- Copenhagen: $<$ **3** kWh/m^2 (South) and $>$ **5** kWh/m^2 (North)
- Rome: $<$ **2** kWh/m^2 (South) and $>$ **4** kWh/m^2 (North)
- Bratislava: $<$ **1** kWh/m^2 (South) and $>$ **3** kWh/m^2 (North)

In comparison, Figure 5.1.4 shows that the savings from reducing the U-value from the reference of 0.5 W/m^{2}K (in Copenhagen and Bratislava) or 1.0 W/m^{2}K (in Rome) to zero were:

- Copenhagen: **5** kWh/m^2 (South) and **9** kWh/m^2 (North)
- Rome: $<$ **2** kWh/m^2 (South) and **5** kWh/m^2 (North)
- Bratislava: **3** kWh/m^2 (South) and **6** kWh/m^2 (North)

These potential savings do not take into account whether or not the solutions would provide sufficient daylighting and thermal comfort.

In the case of Rome, it should be noted that the effect of decreasing the U-value in south-oriented rooms diminished in a similar way to the effect of increasing the g-value. This happened when U-values lower than about **1.0** W/m^{2}K were reached. Furthermore, the small savings in space-heating demand from using U-values lower than 1.0 W/m^{2}K were outbalanced by a small increase in cooling demand that occurred in this climate when the U-value was lowered. A similar increase in cooling demand was observed in the study by Tsikaloudaki et al. (2012).

Finally, Figure 5.1.5 shows that window size had almost no impact on space heating with the glazing properties used as a reference in this case, except in north-oriented parts of the building in Bratislava and Copenhagen. Here, the smaller amount of glazing needed for daylighting when its LT was increased from 50% to 70% reduced space-heating demand by 1–2 kWh/m^2.

The set of key parameters defined assumes that each room can be considered an independent zone. In practice, zones in a real house can take advantage of each other through various degrees of heat and air exchange. As O'Brian et al. (2011) show, heat-exchange due to conduction between zones is less important in this context than heat-exchange due to air flow between zones, which can lead to results for the windows similar to those found with full mixing. Studying the windows on the basis on their performance in isolated parts of the building can be seen as an approach that ensures the window options identified will also perform well in houses where such interaction between zones is limited.

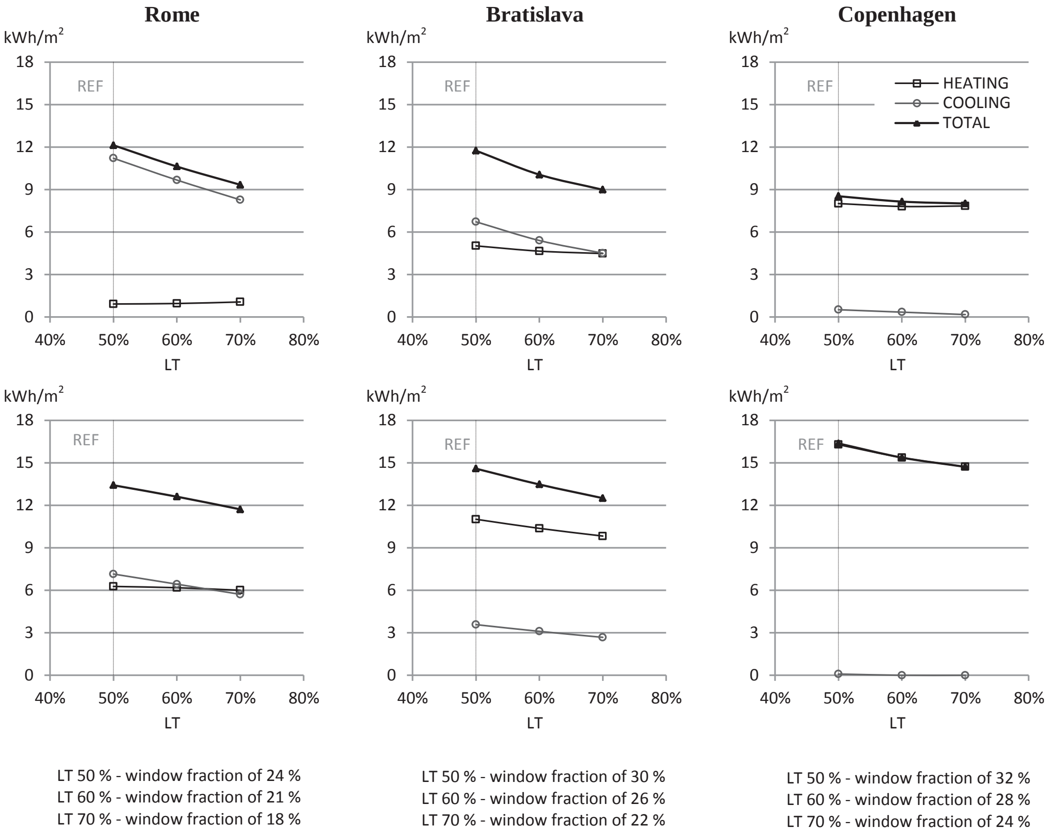


Figure 5.1.5. *Variations in the light transmittance (LT) for glazing oriented south (top row) and north (bottom row) with the corresponding changes in window size needed to maintain sufficient daylighting.*

5.2 Parameter studies on façade windows (P2)

This section presents results from the investigation described in Paper 2 (P2), "*Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses*".

These results are mainly related to the research question Q2: *Can improvements in the energy performance of façade windows be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces?*

To answer this research question, a broad parameter investigation was carried out on the effect of various combinations of window size and glazing properties on energy, daylighting and thermal comfort. The investigation covered a number of north- and south-oriented rooms with various geometries (see Table 5.2.1), located in the middle section of a 1-storey single-family house. The other modelling assumptions can be found in Chapter 4.

The glazing diagram described in Section 3.2 made it possible to visualise the effect of the options investigated within a solution space defined by the criteria for daylighting and thermal comfort. In this case, these were:

- The climate-dependent criterion for daylighting of median DF ≥ 2.1% (see Section 3.1.2).
- The thermal comfort criterion of max. 100 h per year with $T_o > 26$°C (see Section 3.1.3).

For each geometry and orientation, a glazing diagram was made for four glazing U-values in the range of 0.3–0.9 W/m^{2}K. Figure 5.2.1 shows two examples of the use of the solution space based on the results for a single U-value and orientation for the 'base case', a room with a reasonable layout for daylighting with inner dimensions of 4 x 4 x 2.5 m. Figure 5.2.2 shows the results with a U-value of 0.5 W/m^{2}K for a number of the other room geometries to illustrate how the solution spaces were affected by geometry. Finally, to illustrate the effect of the parameters on space heating, Figure 5.2.3 shows the results for the 'base case' with all four U-values.

Table 5.2.1. *Width (W), depth (D) and width-to-depth ratio of the rooms studied.*

	2:1		1.5:1		1:1		1:1.5		1:2	
	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)
Large rooms	8	4	6	4			4	6	4	8
Base case					4	4				
Small rooms	5.3	2.7	4	2.7			2.7	4	2.7	5.3

5.2.1 Solution spaces for the various geometries

The south-oriented room for the 'base case' (top row, Figure 5.2.3) shows that it is possible to find options with sufficient daylighting and thermal comfort (the yellow area) by using windows that are carefully dimensioned for daylighting and have some degree of solar-control coating. This is illustrated by the following two examples, which refer to the options **(1)**–**(3)** shown in Figure 5.2.1 for the windows in the 'base case' with a U-value of 0.5 W/m^{2}K.

Example 1 – Fixed light transmittance (LT)

With a glazing U-value of 0.5 W/m^{2}K, for example, it is possible to achieve a light transmittance (LT) of 70%. A glazing-to-floor ratio of at least 17.8% would then be needed for sufficient daylighting. At this glazing-to-floor ratio, g-values of up to around 0.47 could be used without overheating **(1)**, but the g-value of the glazing could be reduced to almost 0.35 using optimal solar-control coating to improve thermal comfort **(2)**. To use the flexibility of the lower g-value to improve daylighting instead, the glazing-to-floor ratio could be increased to about 23% without overheating **(3)**.

Example 2 – Fixed glazing size (design constraint)

On the other hand, the constraint might be in the design. If the glazing-to-floor ratio is fixed at 25%, for example, the minimum LT for sufficient daylighting would be approximately 48%. With this light transmittance, it would be possible to use a g-value as low as about 0.24 to optimise thermal comfort **(1)**. At this optimum g-value for thermal comfort, the LT cannot be higher, but if the maximum g-value without overheating of about 0.3 **(2)** is chosen instead, it would be possible to use glazing with an LT of up to 60%, which would improve daylighting **(3)**.

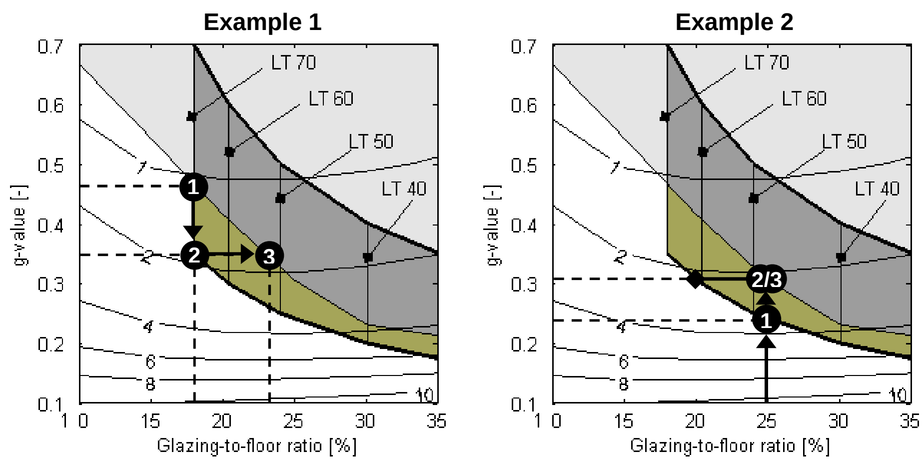


Figure 5.2.1. *Two examples for the 'base case' oriented south with a U-value of 0.5 W/m^{2}K, showing how the solution space in the glazing diagram can be used.*

In north-oriented rooms (bottom row, Figure 5.2.3), the flexibility was large. Here, the window options would mainly be limited by the maximum transmittances that can technically be achieved for well-insulated glazing.

The examples of solution spaces for the other room geometries investigated (Figure 5.2.2) indicate that the 'base case' is rather representative of the flexibility in rooms with a reasonable layout for daylighting. The solution spaces for the two rooms that are either considerably shallower (4 x 2.7 m) or wider (6 x 4 m) are slightly larger than for the 'base case', but similar. For the other two geometries, in contrast, the solution spaces in south-oriented rooms are critically small. In the narrow room with the same depth as the 'base case' (2.7 x 4 m) the solution space is mainly limited by the increased risk of overheating, presumably due the smaller heat loss area in this room. In this case, the flexibility would increase if, for example, a less conservative method for the evaluation of overheating or higher venting rates were used. For the 6 m deep room (6 x 4 m), on the other hand, the lack of options is mainly due to the proportionally larger glazing area needed for sufficient daylighting. For a similar 8 m deep room investigated, sufficient daylighting could not be achieved at all. With the criteria for daylighting and thermal comfort used in Papers 3–5, the flexibility in rooms oriented south would slightly increase, but in rooms oriented north daylighting would be even more difficult to achieve.

In general, the results show that, to achieve sufficient daylighting with façade windows, LTs below 40% (and therefore g-values below 0.2) should be avoided.

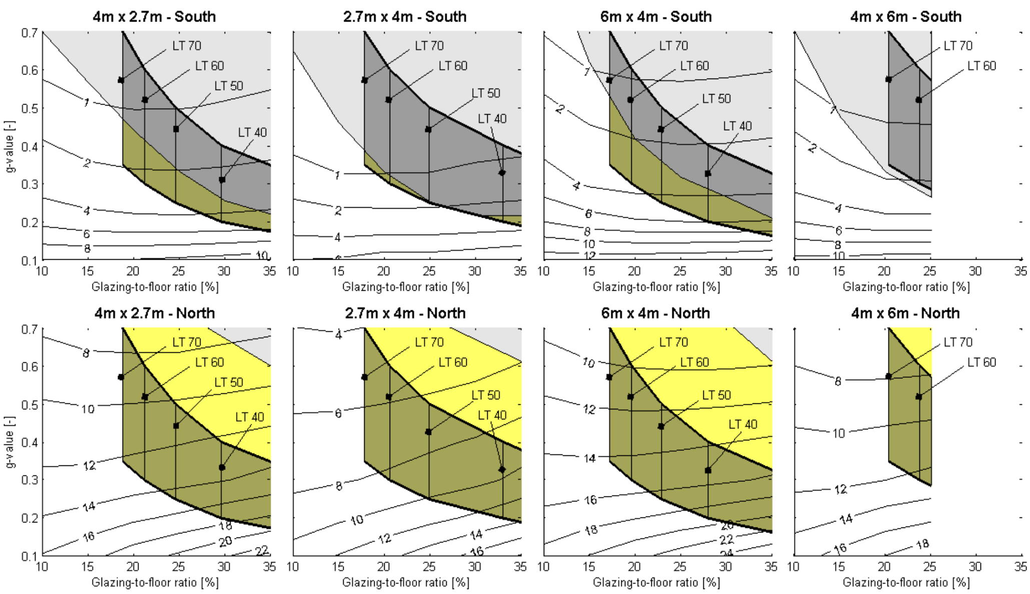


Figure 5.2.2*. Example of results for other geometries with a U_g of 0.5 W/m^2K.*

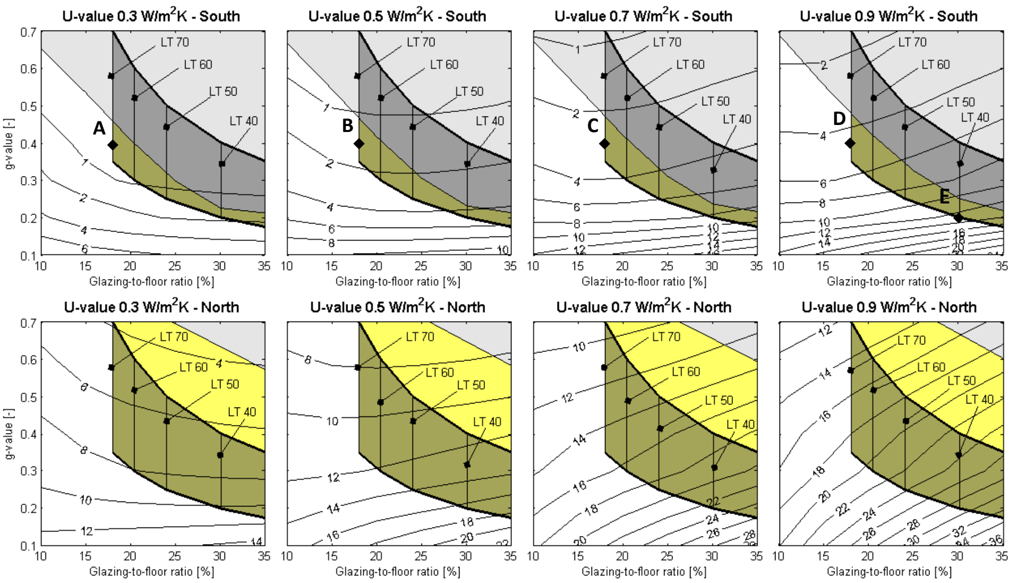


Figure 5.2.3. *Glazing diagrams for the 'base case' with four glazing U-values.*

5.2.2 Effect of parameters within the solution spaces

From the contour lines showing the space-heating demand as a function of g-value and glazing size for the various orientations and glazing U-values for the 'base case' (Figure 5.2.3), some of the main observations were:

- Glazing with high light transmittance dimensioned for sufficient daylighting generally provides the lowest space-heating demand.
- Glazing larger than needed generally increases space-heating demand. Glazing U-values of 0.7 W/m^{2}K and below were needed to achieve an optimum window size for space heating, and the lower the U-value is, the larger the optimum window. With U-values below 0.7 W/m^{2}K, the glazing sizes needed for sufficient daylighting and thermal comfort generally corresponded well with the optimum sizes for space heating, and the consequences of using larger glazing than needed were small.
- The effect of the g-value on space-heating demand is not linear. In south-oriented rooms, the effect of increasing the g-value by 0.1 ranged from 4–5 kWh/m^2 for large glazing with low g-values (Point E) to only 0.2–1.3 kWh/m^2 for typical options with an LT of 70% and a g-value of 0.4 (Points A–D). In north-oriented rooms, the effect of increasing the g-value was more constant, and for the typical options, larger than in south-oriented rooms.

5.3 Parameter studies on roof windows (P3)

This section presents results from the investigation described in Paper 3 (P3), "*Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe*".

These results are mainly related to the research question Q3: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces?* However, the results with regard to the façade windows and to the effect of the roof-window parameters will also be used to answer the research questions Q2 and Q5.

The investigation was based on two room types (Model A and B) located in the middle section of an 8–9 m wide 1½-storey single-family house with a simplified floor plan and a reasonable layout for daylighting in all parts (Figure 5.3.1). The house is oriented north/south, and the two room types are:

- Model A is a side-lit room on the ground floor with two façade windows, similar to the 'base case' studied in Paper 2.
- Model B is a loft room on the 1^{st} floor with two 45°-sloped roof windows in either a north- or a south-oriented roof surface.

Both rooms are 4 x 4 m with an internal room volume of 40 m^3. Model A is thus identical to the 'base case' studied in Paper 2, except that the specific heat loss is approximately 1 W/K lower due to the adiabatic ceiling of the room in this house. The use of sloped roof windows represented by Model B is typical for houses in northern Europe, but is also found in, for example, the top-storey of high-rise apartment buildings in cities all over Europe. The location of the rooms in the middle part of the house means they constitute a relatively difficult case for utilisation of solar gains and achieving thermal comfort compared to being located at one of the building ends. Moreover, it should be noted that the specific house considered here is rather compact in comparison with many other common types of single-family houses, and very well-insulated (see Table 4.1 in Chapter 4).

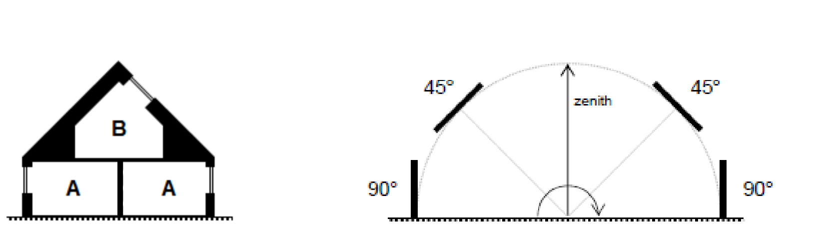


Figure 5.3.1. *Sketch of the rooms A and B in the middle of the 1½-storey house.*

For the two rooms oriented north and south in the climates of Rome and Copenhagen, the glazing diagram (see Section 3.2 and examples of its use in previous section) was used to analyse the space-heating demand with various window options with sufficient daylighting and thermal comfort. The criteria used for the evaluation of daylighting and thermal comfort were:

- The climate-based criterion of at least 300 lx in 75% of the floor space area for 50% of the daylight hours (Spatial coverage of DA 50% $\geq$ 75%).
- The adaptive thermal comfort criterion (Max. 100 h > ATC Limit).

These differ slightly from the more conservative criteria used in Paper 2.

An acceptable space-heating demand for the building section considered was estimated to be about **10 kWh/m^2** per year if the house was to consume nearly zero energy when taking into account the larger heat losses at building ends.

Glazing U-values in the range 0.3–0.9 W/m^{2}K were studied for Copenhagen and in the range 0.7–1.3 W/m^{2}K for Rome. For façade windows (Model A), only one type of frame construction A1 (Table 5.3.1) was considered. It corresponds to the best high-end practice in Denmark. For roof windows (Model B), however, the heat losses associated with the frame construction, and in particular the connections between the frame and roof, were so significant that the thermal properties of frame and junctions were included as a separate parameter to make the results interpretable in practice. The three different frame constructions B1–B3 (Table 5.3.1) that were studied for the roof windows range from the current best standard-practice option (B3), to an option with very low heat losses that does not yet exist (B1).

Figures 5.3.2–5.3.4 show the options mapped for all U-values and frame constructions investigated in Copenhagen, while Figure 5.3.5 shows a selection of results for Rome to visualise the solution spaces.

Table 5.3.1. *Properties of the frame constructions A1 and B1–B3 investigated.*

Window type and slope	Frame construction	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)
Façade 90°	A1 Best high-end practice	0.09	0.8	0.035	0.01	0.583
Roof 45°	B1 Hypothetical	0.09	0.5	0.025	0.01	0.399
	B2 State-of-the art	0.11	0.7	0.025	0.05	0.768
	B3 Best standard practice	0.09	1.5	0.050	0.10	1.460

1) The specific heat loss of the frame, including heat losses through the connections between frame and glazing and between frame and roof. Calculated based on a reference window with outer dimensions of 1.23 x 1.48 m.

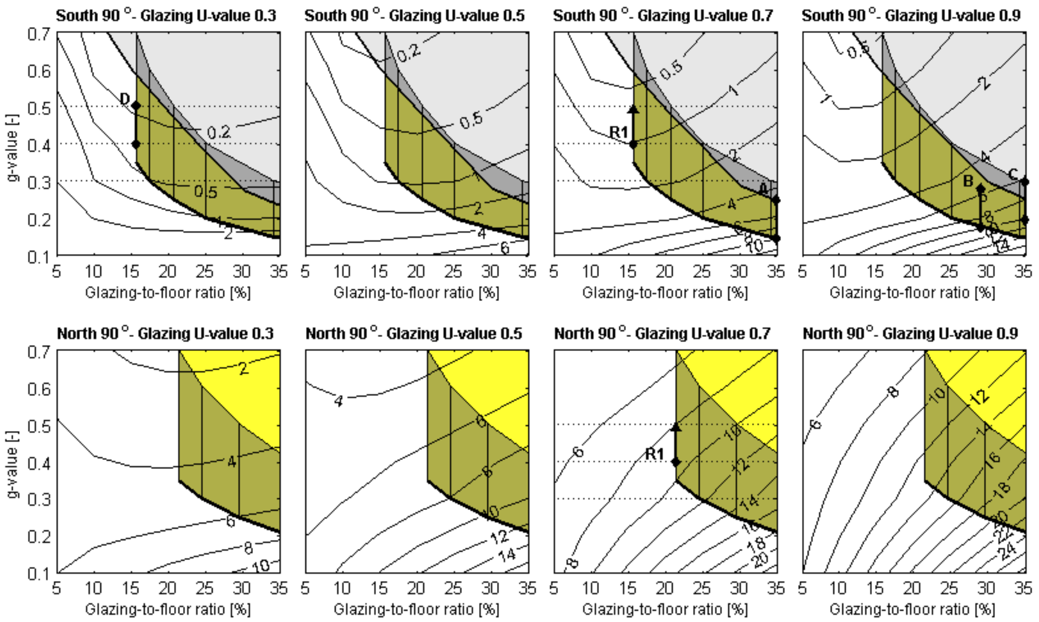


Figure 5.3.2. *Results for the façade windows in Copenhagen oriented south (top) and north (bottom) with the frame construction A1.*

The next sections summarise the findings on the following three topics:

- The solution spaces
- Effect of parameters within the solution spaces
- Example of the thermal properties needed for flexibility

5.3.1 The solution spaces

The solution spaces for the façade windows (Figure 5.3.2) are slightly different from those found for the 'base case' in Paper 2 (cf. Figure 5.2.3). This is due to the different criteria used for evaluation of daylighting and thermal comfort. Differences in minimum glazing sizes for daylighting depend on the climate, the slope of the window and the orientation, but in general the criteria used in Paper 3 give more flexibility due to the less conservative evaluation of thermal comfort.

The solution spaces for the roof windows (Figures 5.3.3–5.3.5) are very narrow for the loft room orientated south in both climates. The design options in these rooms are limited to glazing with a nearly ideal solar-control coating (i.e. with a g-value equal to about half the LT), dimensioned to meet the daylight criterion almost exactly. A typical solar control-coated glazing with an LT of 46% and a g-value of 0.26 (corresponding to Product E shown on the reader's guide to the glazing diagram in Section 3.2), for example, would have to be dimensioned for glazing-to-floor-ratios in the narrow range

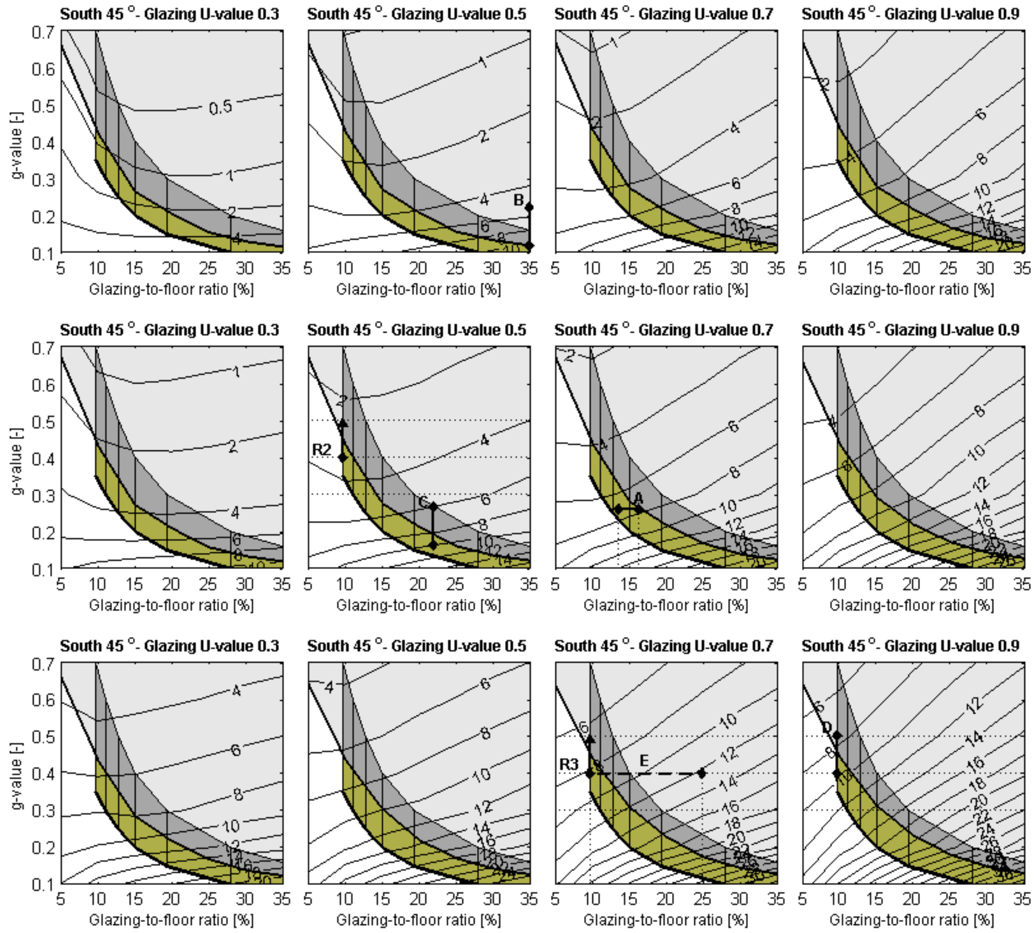


***Figure 5.3.3**. Results for the sloped roof windows in Copenhagen oriented south, with frame constructions B1 (1st row), B2 (2nd row) and B3 (3rd row).*

of 14–16% in Copenhagen and 8–10% in Rome to provide sufficient daylighting without overheating (see Line A in Figure 5.3.3 and 5.3.5). This is given the maximum venting rates assumed of 3 h^{-1} in Copenhagen and 4 h^{-1} in Rome (see Table 4.1 in Chapter 4).

For the north-oriented roof windows, on the other hand, the solution spaces are larger. In Copenhagen (Figure 5.3.4), no selectivity for daylighting was needed for the north-oriented roof windows (i.e. the g-value can equal LT), and glazing sizes could be chosen almost freely without overheating. For example, if a low-energy triple glazing with an LT of 72% and a g-value of 0.51 is used (e.g. Product B in the reader's guide to the glazing diagram), the glazing-to-floor ratios could exceed 35% without overheating (see Line A in Figure 5.3.4). In Rome (Figure 5.3.5), however, the solution space for north-oriented roof windows was similar to that of south-oriented façade windows. This is because a 45°-sloped roof surface oriented north will also receive direct sun in this climate due to the larger solar elevation angles.

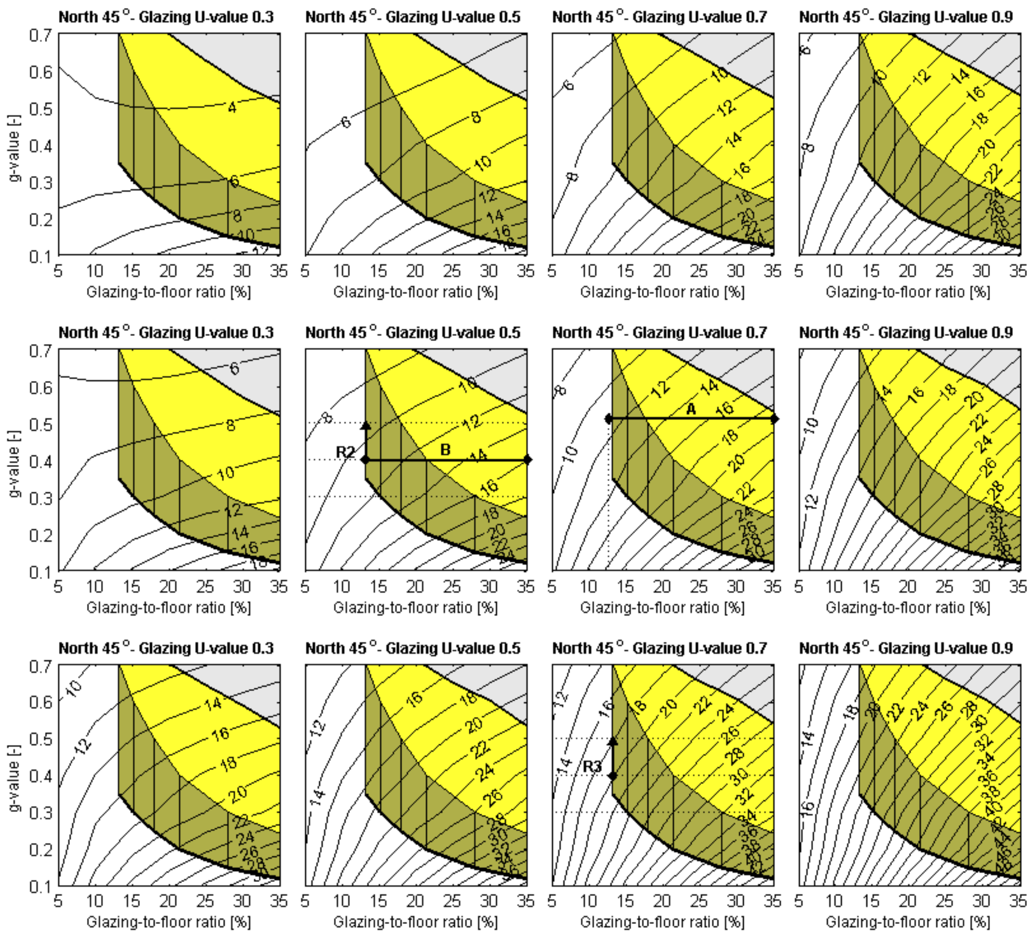


Figure 5.3.4. *Results for the sloped roof windows in Copenhagen oriented north, with frame constructions B1 (1st row), B2 (2nd row) and B3 (3rd row).*

5.3.2 Effect of parameters within the solution spaces

The contour lines showing the space-heating demand of the two window types oriented north and south as a function of glazing size, g-value and the thermal properties of glazing, frame and junctions (Figures 5.3.2–5.3.5) reveals similar tendencies as for the façade windows in Paper 2. Glazing with high light transmittances, when dimensioned for minimum daylighting, generally provides the lowest-space heating demand, and certain thermal properties in glazing and frame are needed to find an optimum glazing size for space heating. For example, if the size of the south-oriented roof windows with standard frame construction (B3) and a glazing U-value of 0.7 W/m^2 in Copenhagen could be increased from the minimum needed for daylighting to a glazing-to-floor ratio of 25% without overheating, this would increase the space-heating demand by 4 kWh/m^2 (see Line E in Figure 5.3.3). With lower U-values, this effect would be smaller. Furthermore, comparison of the space-heating demand for the façade windows in Figure 5.3.2 with the

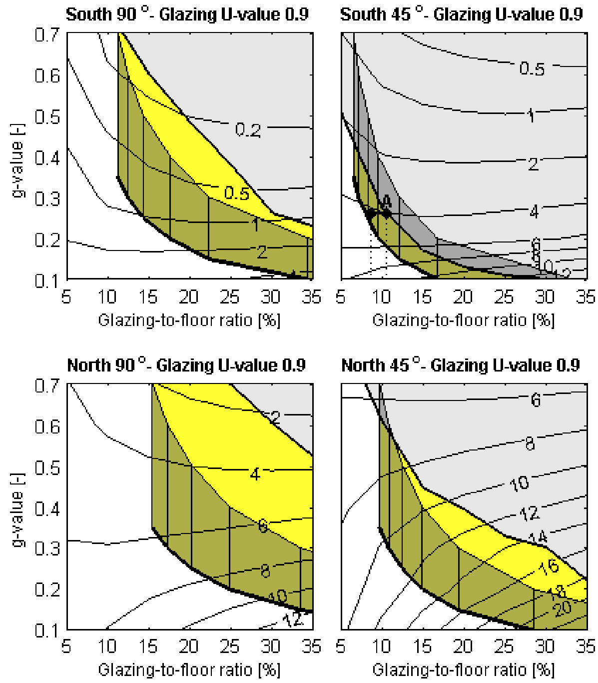


Figure 5.3.5. *Results for façade windows (left) and sloped roof windows (right) oriented south (top) and north (bottom) in Rome, shown for a glazing U-value of 0.9 W/m²K and frame construction B3.*

space-heating demand for the 'base case' in Paper 2 (Figure 5.2.3) shows that the use of larger windows than the optimum for space heating increases space-heating demand most in the room with the smallest heat losses. This indicates that lower U-values are needed for flexibility in the choice of glazing size if the insulation level of the room is improved. In Rome, however, window size had only limited effect on space-heating demand and could be chosen relatively freely within the boundaries for daylighting and thermal comfort. As with the findings from existing research on windows in southern Europe (see Section 2.1.2), large south-facing windows with the lowest U-values could slightly reduce space-heating demand, but the tendency was that large windows with glazing U-values above 0.9 W/m^{2}K oriented either way slightly increased space-heating demand.

Finally, the effect of the g-value is not linear. For large glazing with low g-values and a space-heating demand close to the targeted maximum of 10 kWh/m^2 for the building section considered, the savings in space-heating demand from increasing the g-value in south-oriented rooms in Copenhagen by 0.1 were about 4–5 kWh/m^2 per year (Lines A–C in Figure 5.3.2 and Lines B–C in Figure 5.3.3). However, for more typical window options with an LT of 70% and a g-value of 0.4 dimensioned for minimum daylighting, these savings ranged from less than 0.2 kWh/m^2 for the most-insulated façade window (Line D in Figure 5.3.2) to about 2 kWh/m^2 for the least insulated roof window (Line D in Figure 5.3.3).

Effect of changes in U- and g-value

To make it possible to compare the effect of improvements in glazing U- and g-value for typical options in building parts with different orientations, Table 5.3.2 shows the savings in space-heating demand of either increasing the g-value by 0.1 (dg) or decreasing the U-value by 0.1 (dU_g) with basis in three reference points (R1–R3). These all refer to options with an LT of 70% and a g-value of 0.4 dimensioned for minimum daylighting, but they represent different thermal properties of glazing, frame and junctions (see the footnote to Table 5.3.2). In Copenhagen, R1 corresponds to a façade window with thermal properties somewhere between the best standard practice and the best high-end practice, while R2–R3 correspond to roof window options with thermal properties that are state-of-the art (not yet commonly available) and current best standard practice, respectively. In Rome the reference windows have the same frame constructions, but higher glazing U-values.

With regard to the relative effect of changes in the U- or g-value in Copenhagen, Table 5.3.2 shows that:

- In south-oriented rooms, increasing the g-value by 0.1 reduced space-heating demand by 2 and 2–2.9 times more than decreasing the U-value by 0.1 W/m^{2}K for façade and roof windows, respectively.

- In north-oriented rooms, increasing the g-value by 0.1 reduced space-heating demand by 1 and 1.1–1.7 times more than decreasing the U-value by 0.1 W/m^{2}K for façade and roof windows, respectively.

Table 5.3.2. *Savings in space-heating demand in kWh/m^2 per year from increasing the g-value by 0.1 (dg) or decreasing the U-value by 0.1 (dU_g) for the references R1–R3[1)] with 70% LT and a g-value of 0.4 dimensioned for minimum daylighting. The relative effect of the parameters (dg/dU_g) and the savings as percentage of the targeted maximum space-heating demand of 10 kWh/m^2 (E_t) are also shown.*

Window type and reference[1)]			Rome					Copenhagen				
			dg	dUg	dg/dUg	dg/Et	dUg/Et	dg	dUg	dg/dUg	dg/Et	dUg/Et
Façade 90°	South	R1	0.3	0.1	4.8	3%	1%	0.4	0.2	2.0	4%	2%
	North	R1	1.2	0.5	2.4	12%	5%	1.4	1.3	1.0	14%	13%
Roof 45°	South	R2	0.6	0.1	5.9	6%	1%	0.9	0.5	2.0	9%	5%
		R3	0.9	0.1	7.4	9%	1%	1.8	0.6	2.9	18%	6%
	North	R2	1.0	0.4	2.6	10%	4%	1.3	1.1	1.1	13%	11%
		R3	1.3	0.4	3.4	13%	4%	2.0	1.2	1.7	20%	12%

1) Frame type and glazing U-value (U_g) in W/m^2 K for the references:
- R1 (A1, U_g 1.1), R2 (B2, U_g 0.9), R3 (B3, U_g 1.1) in Rome
- R1 (A1, U_g 0.7), R2 (B2, U_g 0.5), R3 (B3, U_g 0.7) in Copenhagen, as shown in Figures 5.3.2–5.3.4.

According to the simplified methods described in Section 2.1.1, which were found to apply with good accuracy for lightly insulated houses, these relationships were more than 3 for façade windows and 5–6 for sloped roof windows facing south. For the windows facing north they were 0.8 and 1.5. This indicates that south-oriented rooms with nearly zero-energy consumption can only utilize approximately half of the solar gains found almost fully usable in residential buildings. In the case of the north-oriented rooms, the relationships were slightly larger than those found by the simplified methods, which might be due to the simplified heating season these are based on.

With regard to the absolute savings in space-heating demand from improving the U- or g-value in various building parts, Table 5.3.2 shows that the savings from improving both the U-value and the g-value in north-oriented rooms were larger than the savings from improving the g-value in south-oriented rooms. So, even though improvements in the g-value in south-oriented rooms reduced space-heating demand more than improvements in the U-value, these savings in absolute terms were small at building level, due to the difference in space-heating demand between north- and south-oriented rooms.

In Rome, the tendencies were similar. With the lower insulation level of the house and the warmer and sunnier climate, increasing the g-value in south-oriented rooms reduced space-heating demand by about 5 and 6-7 times more than decreasing the U-value. If the saving potentials in different building parts are compared, however, reductions in space-heating demand for changes in both parameters were larger in north-oriented rooms than in south-oriented rooms, but changes in the g-value had considerably larger effect on space-heating demand than changes in the U-value in all cases.

Effect of improvements in frame and junctions

In Copenhagen, the following savings in space-heating demand could be achieved by improving the frame constructions for the two references:

- R3: Replacing the frame construction B3 with B2 would save about 4 kWh/m^2 in south-oriented rooms and 6–7 kWh/m^2 in north-oriented rooms.
- R2: Replacing the frame construction B2 with B1 would save about 2 kWh/m^2 in south-oriented rooms and 3–4 kWh/m^2 in north-oriented rooms.

These savings are 2 or 3 times larger than the largest savings identified with changes in U- or g-value. In Rome, the savings from improving the frame constructions were in the range of 1–2 kWh/m^2.

5.3.3 Example of thermal properties needed for flexibility

Table 5.3.3 shows an example of glazing U-values and frame constructions that would be sufficient to meet the criterion of maximum 10 kWh/m^2 for space heating in the building section considered with two different degrees of flexibility. The example assumes that north- and south-oriented rooms at the ground floor can reasonably meet an average space-heating demand of 6 kWh/m^2 per year, which would permit the loft rooms on the first floor to consume about **16** kWh/m^2 per year for space heating (assuming that they make up 38% of the gross floor area of the house in total).

The two degrees of flexibility used in the example reflect different approaches to the development of windows for nearly zero-energy houses:

Reasonable flexibility

Space-heating demand could generally not be improved by increasing the glazing size, and the maximum g-value of the glazing will be limited either by the physical limitations of the low-energy glazing considered or by the risk of overheating. Certain thermal properties are therefore needed in the glazing and frame to meet the nearly zero-energy targets, and these should be reasonably robust to obstructions from the surroundings or other factors that may reduce glazing transmittances in practice (see the definition of reasonable flexibility in the footnote of Table 5.3.3). For the rooms with south-oriented roof windows in both climates, such flexibility was met with standard frame construction (B3) in combination with all the U-values of the glazing investigated. In Rome, this was also the case for the rooms with north-oriented roof windows. For these rooms in Copenhagen, however, a glazing U-value of at most 0.7 W/m^{2}K and significantly better frame constructions would be needed than are current best standard practice to meet the energy target.

Full flexibility

Another approach would be to focus on improving the thermal properties of the windows to a level where no choice of glazing size or transmittance within the solution space would be critical for meeting the maximum space-heating demand. Products with optimal solar-control coating (i.e. g-values as low as possible without reducing the light transmittance) can provide the best balance between daylighting and thermal comfort, and unlike façade windows, roof windows can provide sufficient daylighting with almost any choice of light transmittance in combination with the right size. Less focus on maximising the g-values in solar exposed rooms would make it possible to use larger glazing in combination with lower transmittances, which could increase architectural freedom and improve daylight distributions.

To achieve such flexibility in the rooms with south-oriented roof windows in Copenhagen, the frame constructions would have to be improved at least to the level of the state-of-the art construction (B2) and at least triple glazing with a U-value of 0.5 W/m^2K would be needed. In north-oriented rooms multi-layer glazing with a U-value of 0.3 W/m^2K would be needed and the frame constructions would have to be improved to the ideal level of B1. In Rome, such flexibility could be achieved in south-oriented rooms with any choice of frame and glazing investigated. In rooms with north-oriented roof windows, however, which might be the most relevant to consider for thermal comfort, either a better frame construction or U-values below 0.7 W/m^2K would be needed to achieve this flexibility.

Solution in between

The use of a roof window with a state-of-the-art frame construction (B2) and a U-value of 0.5 W/m^2K (corresponding to the reference R2) allowed the size of glazing with moderate g-values in north-oriented rooms to be chosen freely without critically affecting the space-heating demand (see Line B in Figure 5.3.4), while it allowed full flexibility in south-oriented rooms.

Table 5.3.3. *Maximum glazing U-values for acceptable space-heating demand in the building section considered with two different degrees of flexibility. The U-values in brackets apply where the energy consumption of north- and south-oriented loft rooms can be averaged.*

Window type and frame construction			Reasonable flexibility 1)		Full flexibility 2)	
			Rome	Copenhagen	Rome	Copenhagen
Façade 90°	-	A1	1.3	0.7	0.7	0.3
Roof 45°	South	B1	1.3 (1.3)	0.9 (0.9)	1.3 (1.3)	0.7 (0.5)
		B2	1.3 (1.3)	0.9 (0.9)	1.3 (1.1)	0.5 (0.3)
		B3	1.3 (1.3)	0.9 (0.5)	1.3 (0.7)	< 0.3 (<< 0.3)
	North	B1	1.3 (1.3)	0.9 (0.9)	0.9 (1.3)	0.3 (0.5)
		B2	1.3 (1.3)	0.7 (0.9)	0.7 (1.1)	< 0.3 (0.3)
		B3	1.3 (1.3)	0.3 (0.5)	< 0.7 (0.7)	Impossible (<< 0.3)

1) Energy target met with 40% LT in rooms with direct sun and 60% LT with a g-value of 0.4 in rooms without direct sun.
2) Energy target met with all combinations of glazing size and g-value within the solution space.

5.4 Permanent vs. dynamic solar shading (P4)

This section presents results from the investigation described in Paper 4 (P4), "*The effect of dynamic solar shading on energy, daylighting and thermal comfort in a nearly zero-energy loft room in Rome and Copenhagen*".

The aim of this investigation was to provide an example of what can be achieved by the use of dynamic solar shading compared to permanent glazing options in very well-insulated homes.

The results are mainly related to the research question Q4: *Can dynamic solar shading make room for more daylighting without overheating? Can dynamic solar shading reduce energy use for space heating?*

If the effects of the shading on transmittances for light and solar energy are considered alone (i.e. potential effects on thermal transmittances are not considered), the direct effects of applying dynamic solar shading would typically be improved thermal comfort, slightly less daylighting, and hopefully no changes in space-heating demand at all. These direct effects can be determined in a relatively straightforward way by comparing the same window option with and without shading. In contrast, the full energy, daylighting and thermal comfort potentials of choosing a dynamic solar shading strategy, (instead of a shading strategy based on non-dynamic glazing options), have to be derived from the flexibility found with each of the shading strategies. To make it possible to answer the research question above, therefore, the glazing diagram (see Section 3.2) was used to map and compare such energy, daylighting and thermal comfort potentials with and without shading for options with acceptable daylighting and thermal comfort.

The investigation was carried out for the same loft room with 45°-sloped roof windows facing south, located in Rome and Copenhagen, as was studied in Paper 3. Table 5.4.1 shows the thermal properties of glazing and frame for the roof windows studied in the two climates.

Table 5.4.1. *Thermal properties of the roof windows studied in the two climates.*

		Glazing U-value	Frame properties				
			Width	U-value	Psi g	Psi w	Specific heat loss[1)]
		(W/m^2K)	(m)	(W/m^2K)	(W/m K)	(W/m K)	(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 connections between frame and glazing and between frame and roof. Calculated based on a reference window with outer dimensions of 1.23 x 1.48 m.

The thermal properties of the roof windows in Copenhagen are equivalent to those of the references R2 (state of the art) and R3 (best standard-practice) studied in Paper 3.

The dynamic shading studied had a shading factor of 0.15 and was activated based on the set-points of 18°C for outdoor air temperature and 300 W/m^2 for total of diffuse and direct solar irradiation. With these control settings, the shading will be activated for about 15% of daylight hours in Copenhagen and for about 35% of daylight hours in Rome. The choice of this shading strategy was made with the aim of finding a solution that improved thermal comfort significantly, while affecting space-heating demand and minimum window sizes for daylighting as little as possible.

For the house as whole to consume nearly zero energy, an acceptable maximum space-heating demand for the loft room was estimated to be about 16 kWh/m^2 per year, and the criteria for daylighting and thermal comfort were:

- The climate-based criterion of at least 300 lx in 75% of the floor space area for 50% of the daylight hours (Spatial coverage of DA 50% $\geq$ 75%).
- The adaptive thermal comfort criterion (Max. 100 h > ATC Limit).

Daylighting above the suggested criterion was quantified in terms of time, so an improvement in daylighting (or daylight autonomy, DA) of 1% means there will be approximately 44 hours more every year with illuminances of at least 300 lx in 75% of the floor space area.

5.4.1 Solution spaces with and without dynamic shading

Figure 5.4.1 shows the solution spaces with and without dynamic shading in the two climates. With regard to the direct effect of dynamic shading, the contour lines for space heating are the same with and without shading, because the dynamic shading did not affect the space-heating demand with the settings chosen. Similarly, the minimum glazing sizes for daylighting increased only slightly in Copenhagen, while they increased more visibly in Rome. With regard to the thermal comfort, however, the use of dynamic shading reduced overheating to a level at which considerably higher g-values could be used in combination with the various glazing-to-floor ratios without overheating. There were therefore more options with acceptable daylighting and thermal comfort (in yellow) with dynamic shading than without.

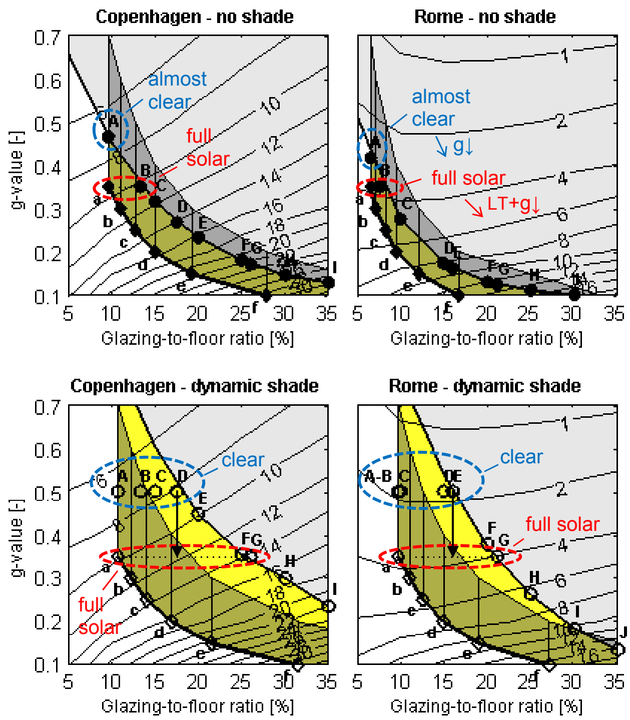


Figure 5.4.1. Solution spaces with and without dynamic solar shading for roof windows with standard thermal properties in Rome and Copenhagen. The evaluation points A-J and a-f enable comparison of potential energy, daylighting and thermal comfort achievements with the two options.

5.4.2 Comparison of potential achievements

To make it possible to discuss what the differences in solution space mean for possible achievements in 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 5.4.1):

- Points A-J represent options at the limits of what is either physically possible or acceptable for thermal comfort. These options have the lowest space heating demand and the best daylighting.
- Points a-f represent options that are just acceptable for daylighting with an LT of 20–70% and optimal solar-control coating. These options have the best thermal comfort.

Figures 5.4.2–5.4.3 show the achievements in energy, daylighting and thermal comfort for these evaluation points in the two climates 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. The light transmittance (LT), g-value and glazing-to-floor ratio of each evaluation point can be found at the bottom of Figures 5.4.2–5.4.3. For simplicity, the maximum LT of all glazing was assumed to be 70% and the maximum g-value was assumed to be 0.5 (see the options referred to as 'clear' in Figure 5.4.1, bottom row). This is realistic for the glazing with U-values of 0.5–0.7 W/m^{2}K in Copenhagen, but a little conservative for the glazing with a U-value of 1.3 W/m^{2}K in Rome.

Limited potential for improving the optimum space heating

Without dynamic shading the lowest space-heating demand in both climates was achieved with the options with an LT of 70% that just met the daylighting and thermal comfort criteria with the highest possible g-value. These are the options with g-values of 0.48 in Copenhagen and 0.42 in Rome, referred to as 'almost clear' in Figure 5.4.1 (see point A, top row). The use of dynamic shading with these options 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 5.4.1). Both these changes could potentially reduce the space-heating demand, but since the change in glazing size either increased space-heating demand or had very limited potential for improving it, the parameter left determining the potential savings in space-heating demand is the g-value. However, the maximum g-value of clear low-energy glazing (assumed to be 0.5), means that only slightly higher g-values could be used with dynamic shading than without (see the options referred to as 'clear' in Figure 5.4.1, bottom row). Comparison of the space-heating demand with and without dynamic shading at point A in Figures 5.4.2–5.4.3 (top-left) 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 by 1.1 kWh/m^2 in Rome. Furthermore, this outcome may be 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 higher 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. Finally, it should be kept in mind that dynamic shading can increase space-heating demand if not properly controlled.

In this way, dynamic shading had limited potential for improving the optimum space-heating demand of the loft room.

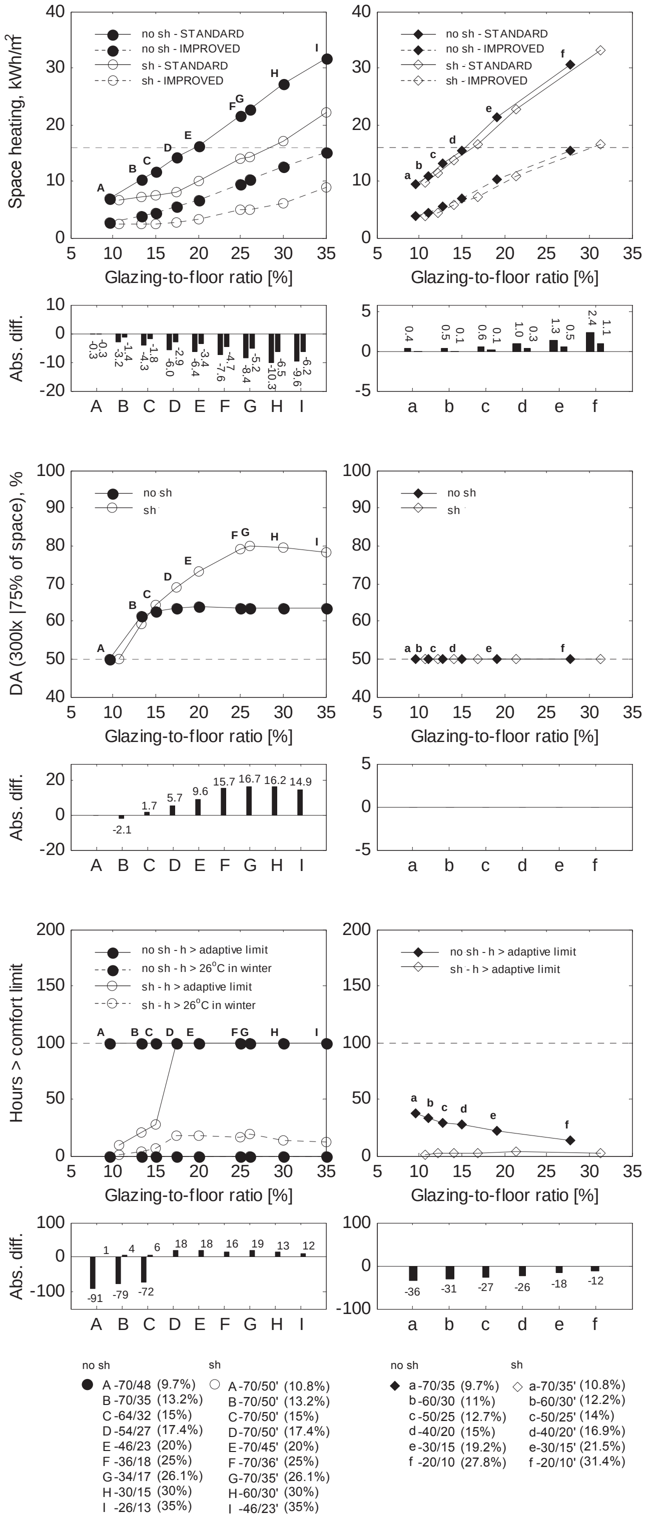


Figure 5.4.2. *Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading for the evaluation points A–I (left) and a–f (right) in Copenhagen. The LT, g-value and glazing-to-floor ratio of the evaluation points are listed at the bottom (see also Figure 5.4.1).*

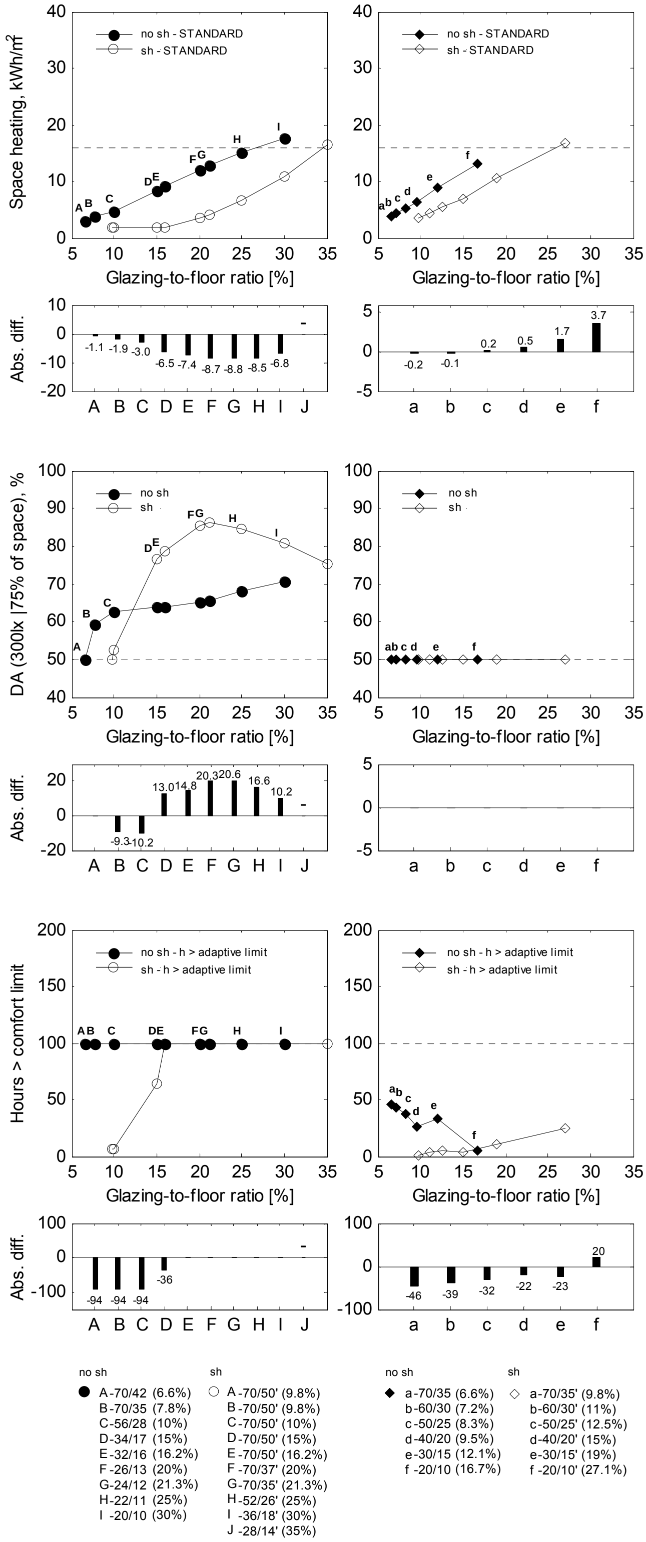


Figure 5.4.3. *Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading for the evaluation points A–J (left) and a–f (right) in Rome. The LT, g-value and glazing-to-floor ratio of the evaluation points are listed at the bottom (see also Figure 5.4.1).*

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 (Figures 5.4.2–5.4.3, top-left). For very large windows, the use of dynamic shading could save up to 9–10 kWh/m^2 per year, but such comparison is not necessarily meaningful for glazing of this size (see Section 5.4.3).

Achievements on daylighting and thermal comfort

If the clearest glazing possible without dynamic shading was used (see point A, referred to as 'almost clear' in Figure 5.4.1, top row), daylighting and thermal comfort were 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.

If solar-control coating, dynamic solar shading, or a combination of both was used, however, options could be found that improved either daylighting or thermal comfort. These options and the achievements in daylighting or thermal comfort can be found described step by step in Paper 5. Here, they are summarised in Table 5.4.2.

For example, Table 5.4.2 shows that the use of optimal solar-control coating alone (see the options referred to as 'full solar' in the table and in Figure 5.4.1, top row) could increase the percentage of daylight hours with sufficient daylighting by 13% in both climates, which corresponds to around 570 more hours with sufficient daylighting than targeted. This improvement was found at glazing-to-floor ratios of 10% in Rome and 15% in Copenhagen using glazing with an LT of around 60% and a g-value of 0.3 (see point C in Figures 5.4.1–5.4.3). If the g-value had instead been lowered to the minimum without increasing the glazing size to more than just needed for daylighting (points a–f), the number of hours with excessive temperatures could have been reduced by at least 50–60 h from the maximum of 100 h.

Table 5.4.2. *Overview of potential achievements in daylighting and thermal comfort with and without dynamic shading. The evaluation points and/or the glazing-to-floor ratios at which the achievements were found are shown in brackets.*

		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)

Table 5.4.2 shows similar achievements with dynamic shading in combination with clear glazing and in combination with glazing with optimal solar-control coating (see the options referred to as 'clear' and 'full solar' in Table 5.4.2 and in Figure 5.4.1, bottom row) along with the glazing sizes and/or evaluation points at which the achievements were found.

In Copenhagen, options with dynamic shading at the comfort limit led to around 20 hours with operative temperatures above 26°C in the winter season (see points D–J, Figure 5.4.2, bottom-left). This was not observed in Rome. While the achievements in daylighting and thermal comfort shown in Table 5.4.2 are based on options at the limits for either daylighting or thermal comfort, however, the flexibility in the solution space could also be used to find a compromise. For example, if option D was used in Copenhagen with a g-value of 0.35 instead of 0.5 (see the arrow in Figure 5.4.1), this would give the same daylighting, while thermal comfort would be significantly improved.

5.4.3 When was one option better than the other?

Dynamic solar shading did not affect the potential to improve the optimum space-heating demand of the loft room in any predictable way. Glazing with high light transmittances dimensioned for just sufficient daylighting generally led to the lowest space-heating demand, and at these glazing sizes (glazing-to-floor ratios of 6.6% in Rome and 9.7% in Copenhagen), the opportunities to use a higher g-value with dynamic shading than without were limited. The main benefits of using dynamic shading in this case would be to improve thermal comfort. However, at a cost of 2–3 kWh/m^2 (see space-heating demand at points A and a in Figure 5.4.1, top row), temperatures exceeding the Adaptive Thermal Comfort (ATC) limit could also be reduced by 50–60 hours without the use of dynamic shading by lowering the g-value to 0.35 (corresponding to optimal solar-control coating).

Both with and without dynamic shading, the percentage of daylight hours with illuminances of 300 lx or more in at least 75% of the floor space area could be improved from the targeted 50% to around 63% in both climates. 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 than with permanent glazing solutions (see point C in Figures 5.4.2–5.4.3, top- and mid-left). Since there may be no reason to increase glazing sizes further without dynamic shading after this maximum for daylighting has been reached, the space-heating demand at point C may be considered the largest comparable energy use without dynamic shading.

The more flexible solution space with dynamic shading made it possible to increase the time with sufficient daylighting by a further 750–1000 hours. About 40% of this improvement in Copenhagen, and 70% in Rome, was found with clear glazing at glazing-to-floor ratios of approximately 16–17% (points D and E). For all window types considered, this part of the improvement would cost less in space-heating demand than the maximum daylighting found using optimal solar-control coating (see points D and E with dynamic shading, and point C without, in Figures 5.4.2–5.4.3, top-left). The maximum improvement in daylighting was found at glazing-to-floor ratios of around 20–25% when using dynamic shading in combination with optimal solar-control coating (light transmittance of 70% and g-value of 0.35). For the window in Rome and the window with improved thermal properties in Copenhagen, the effect of window size was so small that all of this daylighting could be achieved at almost no cost, when compared to the maximum daylighting found when using solar-control coating on its own (see point G with dynamic shading, and point C without, in Figures 5.4.2–5.4.3, top-left).

5.5 Performance in complete houses (P5)

This section presents results from the investigation described in Paper 5 (P5), "*The cost efficiency of improved roof windows in two well-lit nearly zero-energy houses in Copenhagen*".

These results are mainly related to the following research questions:

Q5: *Does the relative importance of roof-window parameters found at room level hold true at building level?*

Q6: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels make it possible to build nearly zero-energy houses in a more cost-effective way?*

To answer these research questions, the investigation considered the effect of changes in the roof windows that are current best standard-practice for two large single-family houses in Copenhagen with typical floor plans (see Table 4.1 in Chapter 4 or Figures 1–2 in Paper 5):

- Case A – a 1½-storey house with 45°-sloped roof windows in the upper storey.
- Case B – a 1-storey quadratic house with horizontal roof windows in the core area.

In both houses, about one third of the floor area depends on roof windows for sufficient daylighting. Case A is a considerably more compact house than Case B (given the transmission areas per internal floor of 2.1 and 2.7). Both houses are considerably more compact than the long and narrow one-storey single-family houses, with façade windows only, commonly found in Denmark.

The two houses were modelled with façade windows corresponding to the current best high-end practice (see Section 5.5.2), and they had air-tight building envelopes with construction details of high quality and the best available heat recovery for ventilation, etc. (see Table 4.1 in Chapter 4). The effect of variations in the roof windows were studied for these two houses, insulated to comply with three different criteria for maximum space heating, where the best corresponds to Danish requirements for nearly zero-energy consumption (see Table 5.5.1). It should be noted that the insulation levels corresponding to the 2010 and 2015 requirements were included only to show how the findings were affected by the space-heating demand of the reference. With the nearly ideal building components assumed in the houses, these should not be taken as reflecting realistic insulation levels for buildings constructed in accordance with 2010 and 2015 requirements.

***Table 5.5.1**. Maximum space-heating demand according to Danish requirements for 2010, 2015 and 2020 (nearly zero-energy), and the U-values needed in the houses with best standard-practice roof windows to just meet these criteria.*

	Case A			Case B		
	2010	2015	2020	2010	2015	2020
Maximum space-heating demand (kWh/m^2)	40.0	22.0	12.0	40.0	22.0	12.0
Space-heating demand of reference (kWh/m^2)	39.9	21.9	12.0	39.7	21.9	12.0
U-value wall (W/m^{2}K)	0.31	0.22	0.14	0.25	0.17	0.10
U-value roof (W/m^{2}K)	0.31	0.18	0.10	0.22	0.13	0.07
U-value ground floor (W/m^{2}K)	0.30	0.18	0.10	0.22	0.13	0.07
Energy saved per cm increased insulation thickness [1)] (kWh/m^{2}cm)	3.5547	1.1468	0.3463	2.5439	0.8417	0.2522

1) Extracted from EnergyPlus simulations of the houses with 25 mm more insulation in all constructions.

The scope for investment in various types of improved roof windows was determined on the basis of the cost of the insulation not needed in the building envelopes to meet the requirements for maximum space-heating demand after installation of the improved roof windows (see Section 3.3).

The interdependency between parameters meant that no approach could be found that would make it possible to address the scope for investment in improved roof windows in a general way that would apply for any type of improvement. However, to make the results reasonably applicable in practice, two types of variation in the roof windows were studied:

1. Variation in the roof-window glazing parameters individually.
2. Variation in the roof windows corresponding to examples of specific improvements: #A–E.

The first type of variation was carried out in such a way that it can be used to estimate the energy-saving potential of an arbitrary improvement in the standard-practice roof windows, with or without solar-control coating. This can be done with good accuracy for improvements consisting of small changes in the parameters combined or changes in one single parameter on its own. Furthermore, the scope for investing in improvements with small energy-saving potentials can be estimated by multiplying the saving potential of the improvement by the cost of saving 1 kWh/m^2 by using more insulation in the houses with standard-practice roof windows (see Section 3.3.1).

For the examples of improvements in the second type of variation, the savings in space heating and the insulation not needed in the houses to achieve an acceptable space-heating demand after installing the improved roof windows were found directly from simulations (see Section 3.3.2).

The results of the two types of variation are described in Section 5.5.1 and 5.5.2 respectively.

While research question Q5 can be answered mainly on the basis of the first type of variation, both types are involved in answering research question Q6.

Finally, the effect of increasing window sizes to more than needed for minimum daylighting and the sensitivity of the scope for investment to changes in the reference houses are briefly addressed in Section 5.5.3.

Before any variations in the roof windows were carried out, the two houses with the best high-end practice façade windows and the best standard-practice roof windows, both with a light transmittance (LT) of 70%, were set up for sufficient daylighting in all parts. Moreover, before studying the specific examples of improvements, all zones met at least the adaptive criterion for thermal comfort of no more than 100 h above the ATC Limit (Section 3.1.3), with a maximum venting rate of 3 h^{-1}.

The two houses were set up for sufficient daylighting and thermal comfort using the information about minimum glazing sizes for daylighting and solar-control coating from the investigations on roof and façade windows at room level summarised in Table 4.4 (see Chapter 4). The procedure is described roughly in Chapter 4, and documented in detail in Paper 5.

Where any change in the roof windows affected the LT of the glazing, the glazing size was adjusted to maintain sufficient daylighting.

5.5.1 Effect of the individual roof window parameters

Figure 5.5.1 (columns 1–3) shows the effect of changes to the glazing U-value (U_g), g-value, and LT (i.e. changes in the glazing size needed to maintain the same daylighting), one at a time, for the roof windows in the two houses. The variations were from the two reference houses with best standard-practice roof windows, in which the g-values for all roof window-glazing corresponded to either no solar control (g-value of 0.5) or nearly ideal solar control (g-value of 0.4). These two scenarios, referred to as 'REF g 0.5' and 'REF g 0.4', were insulated to have the same space-heating demand before carrying out the variations. This was to avoid differences in the space-heating demand of the reference houses affecting the results. For Case A, either 4.8 m^2 south-oriented glazing (1st row) or 5.0 m^2 north-oriented glazing (2nd row) was changed, and for Case B, 6.1 m^2 horizontal glazing was changed (3rd row).

The effect of changes to U_g presented in Figure 5.5.1 can also be used to estimate the effect of changes in the thermal performance of the window in general by treating the heat loss of frame and junctions as projected onto the glazed part of the window, via the total heat loss coefficient U'_g.

The effect of changes in the LT (i.e. glazing size) takes into account the reductions in the U'_g resulting from the effect of frame and junctions being projected onto a larger glazing area as the glazing size increases. If the effect of frame and junctions had been accounted for as a fixed fraction of the window area, the effect of changing the LT would have been larger than in Figure 5.5.1.

Since an improvement will often consist of reductions or increases in all three parameters at once, the right-hand column in Figure 5.5.1 shows the minimum and maximum U_g/g-ratios for which a set of simultaneous changes in the parameters will lead to energy savings. These include the effect of LT, assuming that LT will change by the same amount or up to double as much as the g-value (X = 1 or 2), and are defined as follows:

- Minimum U_g/g-ratio ($|\mathrm{d}g\ -0.1 + \mathrm{X} \cdot \mathrm{dLT}\ -10\%| / |\mathrm{d}U_g\ -0.1|$) for an improvement in U_g to compensate for the simultaneous decreases in g-value and LT (black curves).
- Maximum U_g/g-ratio ($|\mathrm{d}g\ +0.1 + \mathrm{X} \cdot \mathrm{dLT}\ +10\%| / |\mathrm{d}U_g\ +0.1|$) for an improvement in g-value and LT to compensate for the simultaneous increase in U_g (grey curves).

The lower the minimum U_g/g-ratio and the higher the maximum U_g/g-ratio, the easier it is to find a set of changes that improves the energy consumption of the glazing.

The large dotted curves without markers show the relative effect of improving the g-value compared to improving the U_g without considering the effect of LT (dg +0.1/ dU_g −0.1), as known from the simplified methods for energy rating of windows (Section 2.1.3) and as discussed in Paper 3 (Section 5.3.2).

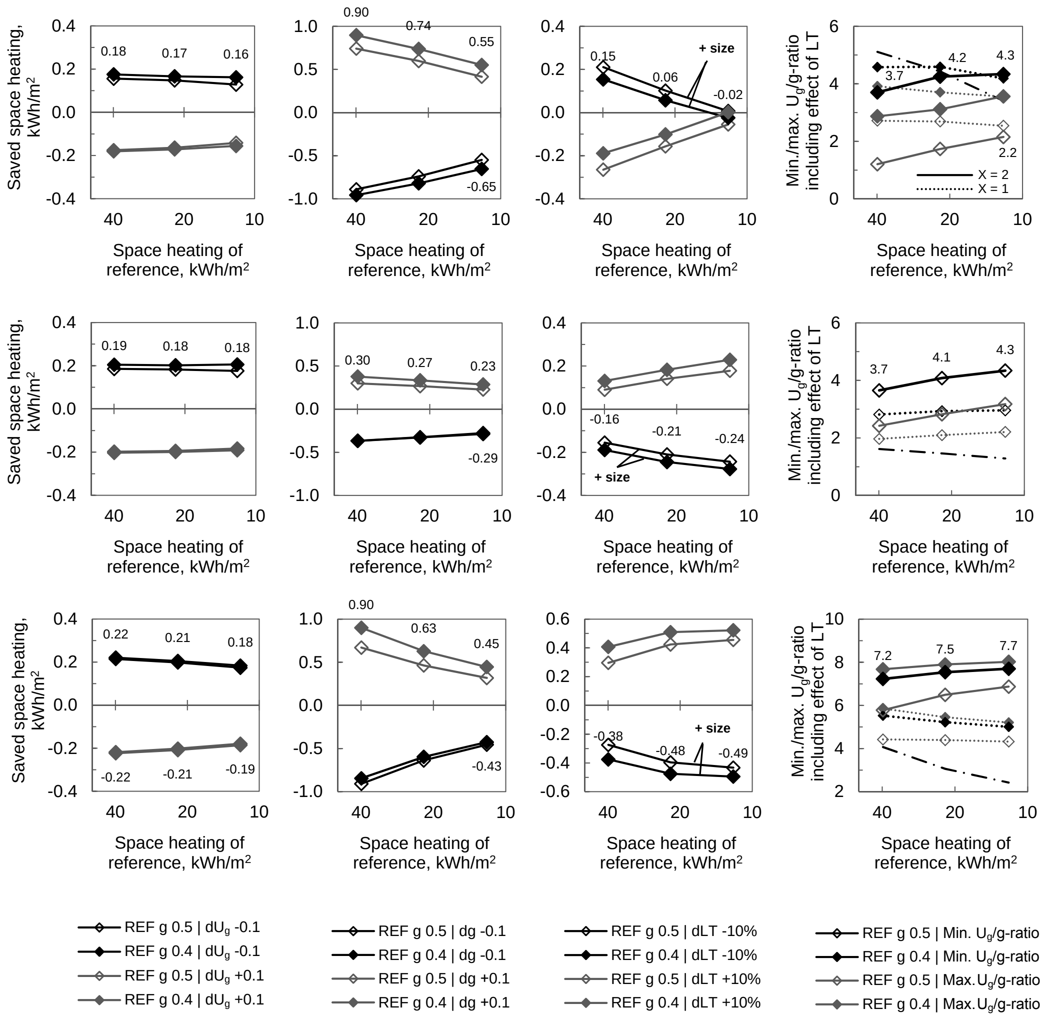


***Figure 5.5.1**. Effect of changes in U_g, g-value (g), and LT (glazing size) for the sloped roof window glazing in Case A oriented south (1st row) and north (2nd row), and for the horizontal roof window glazing in Case B (3rd row). The minimum U_g/g-ratio and the maximum U_g/g-ratio for a set of simultaneous changes in the parameters to save energy are shown in the right-hand column (see the definitions of these ratios in the text). These include the effect of LT, assuming that LT changes by the same amount or double as much as the g-value (X = 1 or 2). The large dotted line in this column shows the relative effect of improving the g-value compared to improving the U_g, excluding the effect of LT. This line and the data labels refer to 'REF g 0.4' (solar control) for horizontal and south-oriented glazing and to 'REF g 0.5' (no solar control) for north-oriented glazing.*

Comparison of the U_g and g-value alone (1^{st} and 2^{nd} column in Figure 5.5.1) shows that the effect of changes in the g-value decreased more rapidly with space-heating demand than the effect of changes in U_g. As a result, improvements in the g-value went from having 4.1 times to having only 2.5 times the effect of improvements in the U_g for the horizontal glazing in Case B (see the large dotted line in the right-hand column). For the south-oriented sloped glazing in Case A, the same relationship changed from 5.0 to 3.4 (and from 3.2 to 2.3 for all roof glazing in this house in total).

With the decreasing ability of the houses to utilise solar gains, the effect of LT (glazing size) changed when going from the highest to the lowest space-heating demand as well (3^{rd} column):

- For the roof windows in Case A facing south, increased glazing size changed from being a way of saving energy to having almost no effect on space heating.
- For the horizontal roof windows in Case B and the roof windows in Case A facing north, increased glazing size led to considerably more space-heating demand at all insulation levels.

If we look at the minimum U_g/g-ratios (black curves) needed for an improvement in U_g to compensate for the simultaneous reductions in both LT (increased glazing size) and g-value, these were considerably higher than the ratios found for the U_g and g-value alone. Moreover, they changed only slightly with insulation level due to the changing effect of window size (LT) and g-value cancelling each other out. A thermal improvement of the glazing, in which the LT decreased by twice as much as the g-value (X = 2), led to energy savings in two houses (consuming nearly zero-energy) if:

- U_g decreased by at least 4.3 times as much as the g-value in Case A (both orientations).
- U_g decreased by at least 7.7 times as much as the g-value in Case B.

For solar-exposed roof glazing in both houses (top and bottom rows), the energy savings from increasing the g-value to above 0.5 (grey curves without fill-in) were 25-30% lower than if the g-value was increased from 0.4 to 0.5 (grey curves with fill-in). The maximum U_g/g-ratios shows that increasing the g-value to above 0.5 (by allowing a higher U_g) could at most compensate for 2-3 and 7 times larger increases in U_g for Cases A and B respectively.

The space-heating demand of zones with roof windows in the two houses was about 11 kWh/m^2 in Case B and 17 kWh/m^2 in Case A. Of the latter, zones with south-oriented roof windows consumed about 13 kWh/m^2, while zones with north-oriented roof windows consumed about 21 kWh/m^2.

5.5.2 Scope for investing in the improvements #A–E

A number of realistic options for improving the roof windows were selected for investigation (#A–E in Figure 5.5.2 and Tables 5.5.2–5.5.3). These range from improvements in the frame and junctions (#B) or the glazed part (#C) alone, to changes that reduced heat losses in all components at once (#D). #A represents the effect of removing the solar-control coating on all solar exposed glazing, and #E represents an improvement whereby the g-value was increased to more than 0.5 by allowing a higher glazing U-value for the sloped roof windows in Case A, in which the combined improvement (#D) is similar to the state-of-the-art product studied in Papers 3–4. For the horizontal roof windows in Case B, which do not necessarily have to be openable, the combined improvement (#D) was taken further to a solution with a 3-pane glazing added at the bottom of the light well. This reduced heat losses through frames and junctions to almost one fifth of those found for the reference window, even though the frame construction itself was not changed (see the specific heat losses in Table 5.5.3). This also offered the potential of letting the glazing added transmit daylight diffusively (#E), which made it possible to reduce the glazing sizes of the roof windows in some of the zones and still maintain sufficient daylighting due to the better distribution of the daylight.

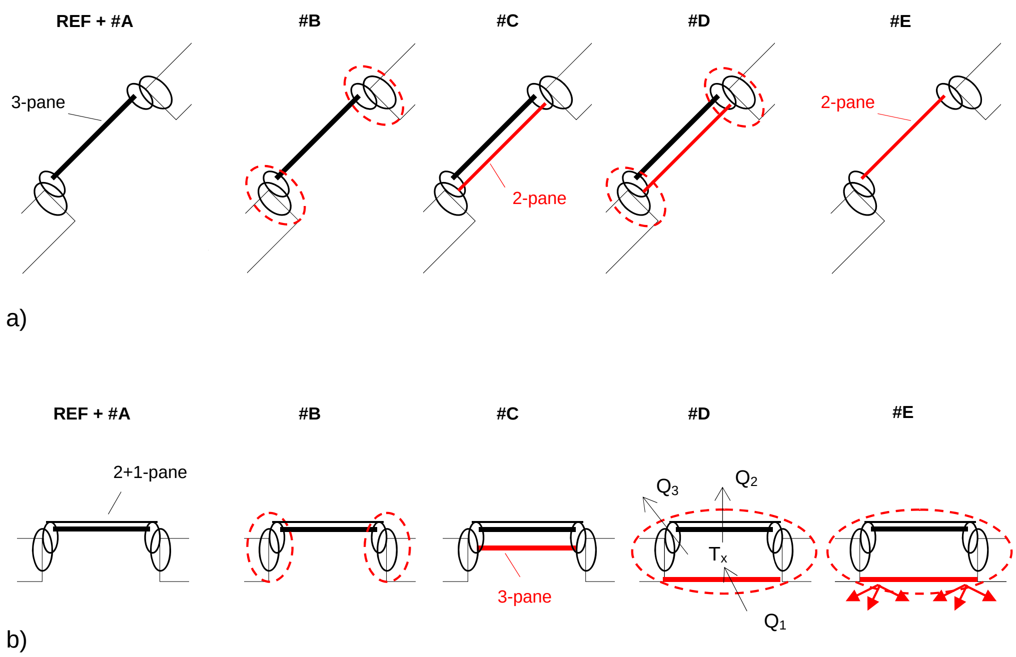


Figure 5.5.2. *Sketch of the options for improving the roof windows investigated for Case A (top) and Case B (bottom), indicating the heat balance approach used to estimate the thermal properties of glazing and frame for the options with the 3-pane glazing added at the bottom of the light well in Case B (improvements #D–E).*

Tables 5.5.2–5.5.3 also specify the properties of the roof and façade windows ('REF') that were used as a reference for studying the improvements. The houses set up for sufficient daylighting and thermal comfort with these windows are also referred to as the 'reference scenarios'.

Figure 5.5.3 (left-hand side) shows the energy savings at building level from replacing the best standard-practice roof windows in the houses with the improved roof windows #A–E. The scope for investing in the improvements per area of improved roof window (as defined in Section 3.3.2) is shown to the right. Figure 5.5.3 also shows in brackets the average changes to insulation thickness and changes in thermal comfort in the most critical zones, after the houses have been insulated for the same energy consumption as before. The thermal comfort for all relevant zones is documented in detail in Paper 5.

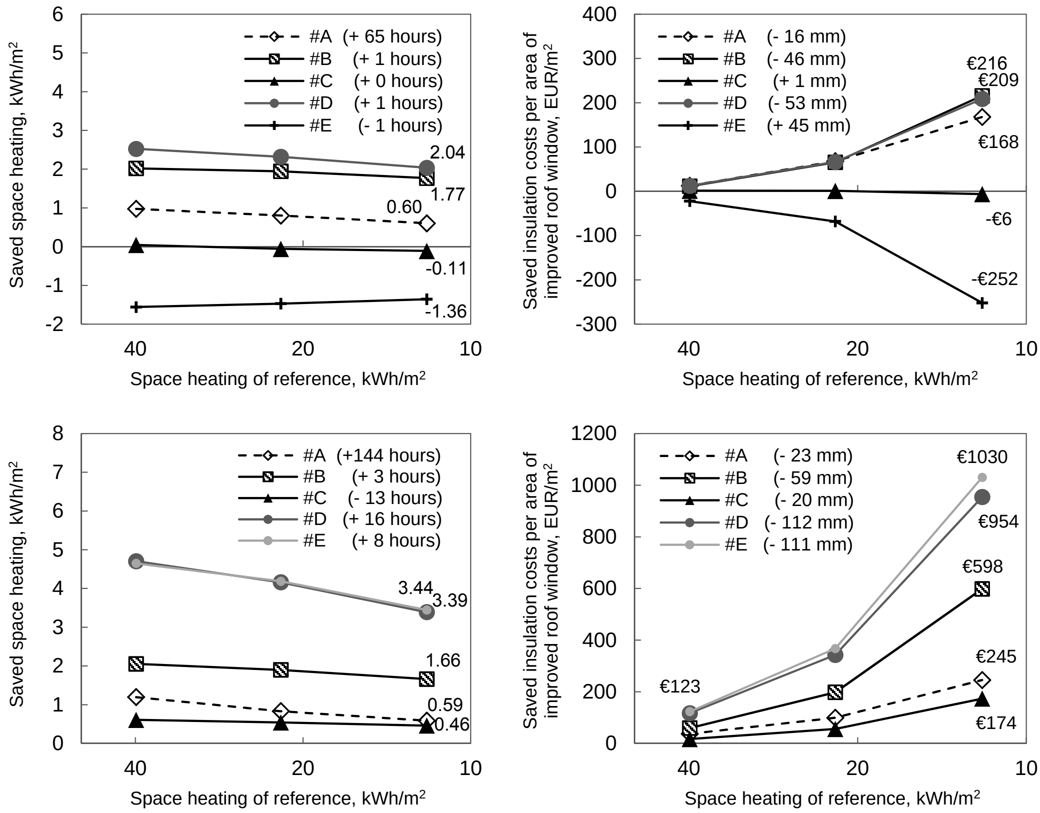


Figure 5.5.3. *On the left: Savings in space-heating demand from replacing the roof windows in the reference scenario with the improved roof windows #A–E for Case A (top) and Case B (bottom). Changes in the number of hours with temperatures exceeding the ATC Limit with a maximum venting rate of 3 h^{-1} in the most critical zones (Zones 1 and 6) are shown in brackets. On the right: The insulation costs saved (i.e. the scope for investment) per area of improved roof window. The average reduction in insulation thickness is shown in brackets.*

Table 5.5.2*. Properties of glazing, frame and junctions for Case A.*

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients 3)		Total window area 4)
			U_g 45°	U_g 90°	g-value 1)	LT	Width	U_f	Psi $_g$	Psi $_w$	Specific heat loss 2)	U_w'	U_g'	A_{win}
			(W/m^2 K)	(W/m^2 K)	(-)	(%)	(m)	(W/m^2 K)	(W/m K)	(W/m K)	(W/K)	(W/m^2 K)	(W/m^2 K)	(m^2)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.92	32.3
Roof	REF	Best standard practice	0.73	0.71	0.39* (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	13.2
	#A	Higher g-value	0.73	0.71	0.50 (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	6.5 5)
	#B	Improved frame and junctions	0.73	0.71	0.39* (0.50)	70	0.11	0.7	0.025	0.05	0.768	0.93	1.35	14.1
	#C	Improved glazing, 2-pane added	0.46	0.41	0.30* (0.40)	55	0.09	1.5	0.050	0.10	1.460	1.15	1.50	16.0
	#D	Improved glazing, frame and junctions (#B+#C)	0.46	0.41	0.30* (0.40)	55	0.11	0.7	0.025	0.05	0.768	0.75	1.02	16.9
	#E	2-pane glazing with higher g-value	1.40	1.10	0.43* (0.60)	78	0.09	1.5	0.050	0.10	1.460	1.85	2.62	11.9

Table 5.5.3*. Properties of glazing, frame and junctions for Case B.*

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients 3)		Total window area 4)
			U_g 00°	U_g 90°	g-value 1)	LT	Width	U_f	Psi $_g$	Psi $_w$	Specific heat loss 2)	U_w'	U_g'	A_{win}
			(W/m^2 K)	(W/m^2 K)	(-)	(%)	(m)	(W/m^2 K)	(W/m K)	(W/m K)	(W/K)	(W/m^2 K)	(W/m^2 K)	(m^2)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.86	31.7
Roof	REF	Best standard practice	1.25	0.90	0.39*	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#A	Higher g-value	1.25	0.90	0.55	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#B	Improved frame and junctions	1.25	0.90	0.39*	70	0.11	0.7	0.025	0.05	0.768	1.29	1.94	9.1
	#C	Improved glazing, 3-pane added	0.50	0.38	0.28*	50	0.09	2.3	0.030	0.10	1.730	1.33	1.81	10.8
	#D	Overall improvement, 3-pane added in the light well	0.50	0.38	0.28*	50	0.09				0.375	0.58	0.79	10.8
	#E	Same as #D, but the added pane is diffuse	0.50	0.38	0.28*	50 diff	0.09				0.375	0.58	0.80	10.1

1) Values representing close-to-ideal solar-control coating (marked with '*') assume that the g-value equals 55% of the LT. Values used for north-oriented glazing with no need for solar control are shown in brackets.

2) Specific heat loss of frame and junctions (including the connections between roof/walls and window) for a window with standard outer dimensions of 1.23 x 1.48 m.

3) U_W' includes all heat loss from glazing, frame and junctions, as projected onto the window area, and refers to the window with standard dimensions above.

U_g' includes all heat loss from glazing, frame and junctions, as projected onto the glazed area, and refers to the area-weighted average of the actual dimensions of the windows inserted in the houses.

Both coefficients are given for the effective slope.

4) Total area of windows inserted in the house.

5) Only south-oriented roof windows were improved.

The following paragraphs presents the findings for the improvements #A–E almost as in Paper 5. The most relevant scopes for investment are listed more comprehensively in the discussion of research question Q6 (Section 6.6).

Removed solar-control coating (#A)

Removing the solar-control coating on the solar-exposed glazing (#A) corresponds to the maximum change in g-value that can usually be achieved without affecting the U_g or LT of the glazing. This improvement led to savings in space-heating demand of 0.6 kWh/m^2 in both houses, which is slightly more than the savings achieved for the best of the thermal improvements in the glazing. However, while all the other improvements provided similar thermal comfort as for the reference scenario, this improvement considerably increased the time with excessive temperatures (see Figure 5.5.3). The insulation costs of about EUR 200 saved by removing the solar-control coating might therefore have to cover the cost of the installation and maintenance of dynamic solar shading devices or other means of avoiding overheating.

Thermal improvements to the glazing (#C)

The thermal improvement in the glazing (#C) in Case A, with a U_g/g-ratio of 3.9 (see changes in g-value and U'_g in Table 5.5.2) turned out almost neutral. The considerably better improvement for Case B (U_g/g-ratio of 8.7), on the other hand, led to savings in space-heating demand of 0.5 kWh/m^2, which is reasonable with the minimum U_g/g-ratio needed for the windows in this house of 7.7 (see Section 5.5.1). The improvement reduced the insulation costs by EUR 170 per area of improved roof window. Assuming two replacements of sealed glazing units over the lifetime of the insulation, the improved window may cost EUR 50–60 more per m^2 than the windows that are standard practice today.

A similar scope for investment or more could be expected from using this improvement in Case A, where the energy-saving potential would be at least the double (see Figure 5.5.1), while the cost of saving energy by using more insulation in this house would be almost the half (see Section 5.5.3).

Glazing with higher transmittances? (#E – Case A)

The increase in g-value from using the 2-pane glazing in Case A (#E) could not compensate for the 8 and 19 times larger increase in U_g, and space heating considerably increased. According to Figure 5.5.1 (Section 5.5.1), the U_g/g-ratio for this type of improvement to save energy should have been at most 1–2 (north, X = 0.8) and about 4 (south, X = 2), which could not have been achieved even without the solar-control coating on south-oriented glazing.

Improved frame and junctions (#B)

The improvements in frames and junctions alone (#B), which corresponded to changes in U'_g for the inserted glazing of 0.52 W/m^2 K for Case A and 0.83 W/m^2 K for Case B (see Tables 5.5.2–5.5.3), led to energy savings of 1.7–1.8 kWh/m^2 in the two houses. This reduced insulation costs per area of improved roof window by around EUR 200 in Case A and EUR 600 in Case B, which would probably have to cover at most one replacement, if the sealed glazing units can be replaced separately.

Combined improvements (#D)

The combined improvement in Case A (#D) shows the effect of improving the frame and junctions (#B) and the glazing (#C) at the same time. This resulted in slightly more energy savings than improving the frame and junctions alone (#B), even though the improvement in the glazing itself (#C) was found to have a neutral or slightly negative effect on space heating. The glazing improvement had a positive effect on space heating when combined with the improvement in frame and junctions because of the way the consequences of increased glazing size decrease with improved thermal properties (see Section 5.5.3). However, the scope for investment of EUR 200 per area of improved roof window hardly changed at all because the savings were distributed onto a larger window area (see Table 5.5.2).

The combined improvement in Case B (#D), where a 3-pane glazing was added at the bottom of the light well, reduced space-heating demand by 3.4 kWh/m^2, which is twice the energy saved by improving the frame alone (#B), even though the frame construction itself was not changed. On average, this relatively simple improvement would save the building owner more than 100 mm insulation throughout the house and reduce the insulation costs by EUR 950 per area of improved window. If this amount has to cover at most two replacements, the improved roof window could cost EUR 310–320 more per area than the windows that are best standard-practice today.

Glazing with diffuse transmittance (#E – Case B)

If the 3-pane glazing added at the bottom of the light well in Case B was replaced with glazing that transmits daylighting diffusively (#E), slightly less glazing area was needed for sufficient daylighting in Zones 1, 6 and 9. This led to slightly improved thermal comfort and a scope for investment of EUR 80 more per m^2 of improved window than for #D. This exemplifies a permanent approach for improving thermal comfort beyond what can be achieved with solar-control coating.

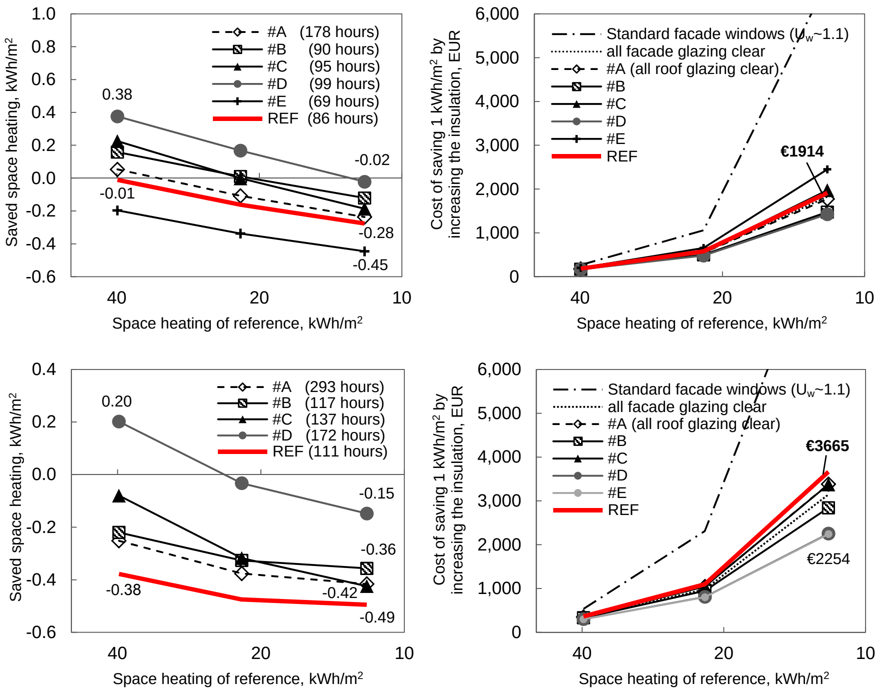


Figure 5.5.4. *The effect of increasing the glazing sizes corresponding to a change in LT of -10% (left) and the cost of saving 1 kWh/m^2 by usig more insulation for various scenarios insulated for the same space heating (right). The number of hours with temperatures exceeding the ATC Limit with a maximum venting rate of 3 h^{-1} in the critical zones are shown in brackets. Case A (top) and Case B (bottom).*

5.5.3 The sensitivity and application of the findings

Figure 5.5.4 (left-hand side) shows that increasing the glazing sizes to more than needed for sufficient daylighting affected space heating less with the improved roof windows than with the current best standard-practice roof windows, even though all scenarios were insulated for the same space-heating demands before changing the size. This means that improved roof windows would make it cheaper for building owners to use larger windows where possible without overheating, and improvements in the glazed part that reduce LT will tend to perform better when the overall improvement is large.

Figure 5.5.4 (right-hand side) shows that removing the solar-control coating on all roof or façade window glazing would only slightly affect the scope for investments. In contrast, if the reference scenario had had considerably less well-insulated façade windows, this would more than double the scope for investment. Moreover, an estimate in Paper 5 showed that the scope for investment in large improvements may be overestimated by up to EUR 200 if derived from the energy saved by the improvement times the cost of saving 1 kWh/m^2 by using more insulation for the reference scenario (Section 3.3.1).

Chapter 6

Discussion of the research questions

This chapter discusses the answers to the research questions Q1–Q6 based on the findings from the investigations presented in Chapter 5.

6.1 Research question 1 (Q1)

This section discusses the research question, Q1: *Can the space-heating demand of nearly zero-energy houses be represented by a few key parameters?*

The answer to this research question is 'yes'.

In general, the heating demand of a space can be said to be governed mainly by its total specific heat losses, the slope, orientation and effective aperture of the windows (defining the solar energy transmitted), the internal loads, the thermal capacity and the climate. For the purpose of studying the windows, however, it is convenient to keep the parameters related to the windows separate from the rest of the building envelope. The heating demand of a given space in a given climate would then depend on:

- Glazing U-value (including heat losses from frame and junctions)
- Glazing g-value (including shading and obstructions)
- Glazing size
- Glazing slope and orientation

- Specific heat losses due to ventilation, infiltration and transmission in the rest of the building envelope
- Internal heat gains
- Thermal capacity

The same is true in nearly zero-energy houses. As a simplification in the present study, a constant heat load from people and equipment was assumed and the thermal capacity was considered a rather fixed parameter, which was not further investigated. Moreover, with the assumptions made to achieve very low energy use in nearly zero-energy houses (described in Paper 1), the main variables determining the space-heating demand were limited to just the parameters related to the windows and the specific heat losses of walls, roof and floor.

With regard to the parameters related to windows, Paper 1 showed that the space-heating demand in both north- and south-oriented parts of a nearly-zero energy house varied continuously with changes in the glazing U-value and g-value. Results from previous research on windows in very well-insulated houses as well as from the investigations described in Papers 2–4 in the present research show that this is also the case with regard to the glazing size.

With regard to the specific heat losses of constructions, the way they affect space heating is well-known. However, while parametric analyses carried out for lightly insulated houses have shown that the relative effect of the window parameters could be studied rather independently from the parameters related to the rest of the building (Sullivan and Selkowitz, 1985a), this is not the case for nearly zero-energy houses. The utilisation of solar gains depends on the overall heating needs of a space. Therefore, any change in the parameters affecting the overall space-heating demand in rooms or houses where not all solar gains are needed will also affect the relative effect of the window parameters. In the present research this dependency was observed most clearly in the window parameter variations carried out for the houses with three different insulation levels studied in Paper 5.

This means that the effect of the windows on space-heating demand in nearly zero-energy houses cannot be studied in terms of variations in the window parameters alone. The effect of variations in the overall space-heating demand has to be taken into account in the analyses as well.

6.2 Research question 2 (Q2)

This section discusses the research question, Q2: *Can improvements in the energy performance of façade windows be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces?*

The answer to this research question is 'yes'.

The glazing diagram introduced in Paper 2 made it possible to map and visualise the various combinations of light transmittances (LT), g-values, and glazing-to-floor ratios that would lead to sufficient daylighting without overheating in rooms with windows of a certain slope and orientation. The results from studying rooms with various geometries in Paper 2 showed that such options with sufficient daylighting and thermal comfort existed for façade windows as long as they were located in rooms with a reasonable layout for daylighting (i.e. rooms that are not too narrow or deeper than about 4–5 m). In south-oriented rooms, this required windows dimensioned for almost exact fulfilment of the daylight target and close to ideal solar-control coating (i.e. with a g-value equal to approximately half of the LT). This was when daylighting and thermal comfort were evaluated on the basis of the most conservative criteria used throughout this study for south-oriented windows. When the climate-based criterion for the evaluation of daylighting and the Adaptive Thermal Comfort (ATC) model for evaluation of thermal comfort were used (Paper 3), the options with sufficient daylighting and thermal comfort in south-oriented rooms were considerably greater. In north-oriented rooms with a reasonable layout for daylighting, the flexibility was generally large.

The glazing diagram also made it possible to study the effect of these options on space-heating demand.

6.3 Research question 3 (Q3)

This section discusses the research question, Q3: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces?*

The answer to this research question is 'yes'.

Results from Paper 3 showed that improved frame constructions and glazing U-values in the 45°-sloped roof windows studied would:

- Increase flexibility in the choice of window size.
- Lead to better correspondence between the window sizes needed for sufficient daylighting and thermal comfort and the window sizes with the lowest space-heating demand.
- Make it possible to use rooms with north-oriented roof windows to the same extent or more as rooms with south-oriented roof windows.
- Make it possible to use larger glazing with lower light transmittances (and the appropriate solar-control coating) in south-oriented rooms.

In the climate of Copenhagen, improvements in either glazing or frame beyond current best-standard practice were found rather critical for flexibility in the building design. For example, if an option such as a roof window with a state-of-the art frame construction (B2) and glazing U-value of 0.5 W/m^2 could be made commonly available (i.e. reference R2 studied in Paper 3), this would make it possible to have rooms with north-oriented roof windows of any size (up to glazing-to-floor ratios of 35%) almost freely and still have nearly zero-energy consumption. If south-oriented roof windows were used, this options's thermal properties would make it possible to have nearly zero-energy consumption with glazing of any size and transmittance within the solution space for daylighting and thermal comfort.

These findings are based on the specific case of a compact and very well-insulated house with a simplified floor plan and no air- or heat-exchange between zones. However, given the compactness and insulation level of the house, the example may be considered a strong indication of a need for improved roof windows if such flexibility in building design is to be achieved.

In the climate of Rome, improvements in the thermal properties of glazing and frame would also increase flexibility, but better options than the windows with glazing U-value of 1.3 W/m^2 and the current best standard-practice frame construction were not critical for design.

Furthermore, the investigation carried out to answer this research question demonstrated some important effects, which may be found in nearly zero-energy houses where the interaction between zones with different orientation is limited. Due to the differences in space-heating demand between north- and south-oriented rooms, more energy could be saved by increasing the g-value or decreasing the U-value of typical windows in north-oriented rooms than by increasing the g-value of typical windows in south-oriented rooms. The south-oriented rooms could also utilise only about half of the solar gains found almost fully usable in lightly insulated houses. Although the effect on space-heating demand of changing the g-value in south-oriented rooms was still greater than that of changing the U-value, the lower utilisation means that it might be easier than previously thought to improve the U-value of the glazing without the simultaneous reduction in the g-value cancelling out the overall energy savings.

With regard to the solution spaces for roof windows, it should be noted that, assuming a maximum venting rate of 4 h^{-1} in Rome and 3 h^{-1} in Copenhagen, the options that provided sufficient daylighting and thermal comfort with sloped roof windows facing south were limited to glazing dimensioned for nearly exact fulfilment of the daylight target and close to ideal solar-control coating (i.e. with a g-value equal to about half of the LT). However, unlike façade windows, roof windows of the right size could provide sufficient daylighting with almost any choice of light transmittance due to their flexibility in placement. Investigations made in connection with an initial version of Paper 3 showed similar solution spaces for horizontal roof windows. In Rome, the solution spaces found with horizontal roof windows were about equal in size to those with sloped roof windows facing south, while in Copenhagen, slightly more flexibility was found with horizontal roof windows than with sloped roof windows facing south, when comparing rooms with a similar insulation level. Better thermal properties in windows cannot increase the options with regard to sufficient daylighting and thermal comfort, but would make it possible to choose more freely amongst these options and still achieve nearly zero-energy consumption.

6.4 Research question 4 (Q4)

This section discusses the research question, Q4: *Can dynamic solar shading can make room for more daylighting without overheating? Can dynamic solar shading reduce energy use for space heating?*

The answer to the first part of this research question is 'yes'.

The investigation described in Paper 4 showed that the more flexible solution space with dynamic shading than without made it possible to either increase daylighting by 750–1000 h or reduce the number of hours with temperatures exceeding the comfort limit as defined by the ATC model by 40–50 h.

However, it should be kept in mind that illuminances of 300 lx in 75% of the floor space area could also be achieved in 50–63% of the daylight hours with no more than 40–100 h with excessive temperatures by means of solar-control coating on its own (i.e. no dynamic shading). Dynamic shading did not make room for more daylighting before glazing-to-floor ratios of more than 10% in Rome and 15% in Copenhagen. It should also be noted that only part of the increase in daylighting made room for with dynamic shading was found with clear glazing. The maximum improvement in daylighting was found at glazing-to-floor ratios of 20–25% when the dynamic shading was combined with optimal solar-control coating.

The answer to the second part of the research question is 'no' for Copenhagen and 'yes' for Rome.

As concluded in Paper 4: "Dynamic solar shading did not affect the possibility of improving the optimum space-heating demand of the loft room in any predictable way". The lowest space heating demand in the loft room was generally achieved using roof windows with a light transmittance of 70% dimensioned to just fulfil the daylight criterion, and at these glazing-to-floor ratios (6.6% in Rome and 9.7% in Copenhagen), the maximum g-values that could be used in the two climates without dynamic shading and without overheating were not much lower than the maximum g-value of 0.5 assumed for the glazing considered. In this way, dynamic shading showed little potential for improving the optimum space-heating demand of the loft room.

In Copenhagen, this conclusion is based on roof windows with thermal properties that are the best standard-practice and state-of-the art today. For these windows g-values higher than the maximum of 0.5 assumed are not realistic, and larger windows generally increased space-heating demand. The investigations in Paper 5 also showed that it was not possible to reduce space-heating demand by using a higher g-value combined with a higher U-value.

In Rome, on the other hand, where the roof windows studied in the paper had only double-glazing, larger windows with better thermal properties could potentially reduce space heating. Moreover, the g-value of the double-glazing considered could have been slightly higher than the maximum of 0.5 assumed in the comparisons. In this way, the use of dynamic shading may hold some room for improving the optimum space-heating demand in Rome.

However, irrespective of the answer to the second part of the research question, it can be argued that the motivation for using dynamic shading in either climate, and especially in Rome, should be to improve daylighting and thermal comfort rather than reducing the space-heating demand. The investigation carried out to answer this research question demonstrated how the use of solar-control coating, with or without dynamic shading, led to quantifiable improvements in either daylighting or thermal comfort. Given the challenge of finding a balance between sufficient daylighting and thermal comfort, it may therefore be wiser in either case to choose a glazing with optimal solar-control rather than the clearest glazing possible without overheating. In the case of the loft room considered, the cost in space heating of using solar-control coating instead of clear glazing was about 2–4 kWh/m^2 per year. If the thermal properties of the windows are at a level where such an increase in space-heating demand will not be critical for nearly zero-energy consumption, a very low energy use and an optimal balance between daylighting and thermal comfort can both be achieved at the same time.

6.5 Research question 5 (Q5)

This section discusses the research question, Q5: *Does the relative importance of roof-window parameters found at room level hold true at building level?*

The answer to this research question is both 'yes' and 'no'.

Nothing indicates that the relative effect of parameters found at room level does not hold true for the type of houses the rooms are intended to represent. However, comparison of the results from variations in the sloped roof windows in Copenhagen studied in Papers 3 and 5 demonstrated how differences in floor plan between houses with the same overall energy consumption may considerably affect the space-heating demand of the zones with roof windows. This in turn affected the relative importance of the roof-window parameters.

The results compared were both based on the current best standard-practice roof windows with a light transmittance of 70% and a g-value of 0.4 dimensioned for minimum daylighting (see 'R3' in Table 5.3.2 and 'REF g 0.4' in Figure 5.5.1). In Paper 3, these windows are located in simple loft rooms with only roof windows oriented either north or south. A 1½-storey house with an equal number of these loft rooms oriented north and south will just consume nearly zero energy. In Paper 5 (Case A), the roof windows are located in more diverse zones in a 1½-storey house consuming nearly zero energy with a typical floor plan. The only difference between the windows compared is that the glazing-to-floor ratios for minimum daylighting were on average about 4–6% higher in the house studied in Paper 5 than in the loft rooms studied in Paper 3.

Table 6.5.1 shows the effect on space heating of increasing the g-value by 0.1 compared to decreasing the U-value by 0.1 W/m^2K for the roof windows studied in Papers 3 and 5 oriented north and south, and combined. These relationships can be seen as a measure of the utilisation of solar gains.

***Table 6.5.1**. The effect on space heating of increasing the g-value by 0.1 compared to decreasing the U-value by 0.1 W/m^2K as found in Papers 3 and 5 for sloped roof windows with the same properties. The right-hand column also shows this measure as found using the simplified methods reviewed in Section 2.1.3.*

Window type and orientation		Paper 3	Paper 5	Simplified methods[1)]
Roof windows 45°	S	2.9	3.4	4.1 – 5.7
	N	1.7	1.4	1.1 – 1.5
	House/ N+S	2.1	2.3	2.6 – 3.6

1) Depending on heating season (see Table 2.1.1 in Section 2.1.3).

The relationships found for the two cases were not expected to be identical. The loft rooms studied in Paper 3 were intentionally located in the middle section of the house considered so that they would represent a situation where the risk of overheating is large. With less heat loss in these rooms than in the rest of the storey, the utilisation of solar gains was also expected to be lower than the average. However, comparison of the relationships in Table 6.5.1 shows that the overall utilisation of solar gains for the roof windows was quite similar for the two cases (despite the differences expected), while the utilisation of solar gains for the south-oriented roof windows was considerably larger in the house with a typical floor plan (Paper 5) than in the loft room studied in Paper 3. Similarly, the overall space-heating demand in zones with roof windows turned out almost equal for the two cases (17 kWh/m^2 in Paper 5 and 16 kWh/m^2 in Paper 3), while the space-heating demand in zones with south-oriented roof windows was considerably larger in the house with a typical floor plan studied in Paper 5 (about 13 kWh/m^2) than in the south-oriented loft room studied in Paper 3 (about 8–10 kWh/m^2).

This made improvements in the south-oriented roof windows in the house with a typical floor plan studied in Paper 5 significant at building level (see Figure 5.5.1). Moreover, while larger windows facing south considerably increased space heating in the loft room studied in Paper 3 (see Figure 5.3.3), the size of these windows in the house with a typical floor plan had almost no impact on space-heating demand (Figure 5.5.1).

These differences do not change the conclusions on the need for roof windows with improved thermal properties to achieve flexibility in building design, including the flexibility needed to choose the best options for daylighting and thermal comfort in houses where interaction between zones is limited. Furthermore, if comparing the effect of parameters found in Paper 3 with the effect of parameters found in Figure 5.5.1 for a space-heating demand of the reference that corresponds better with that of the loft rooms studied in Paper 3, the relationships between parameters for the two cases are similar.

However, when it comes to estimating the saving potentials of the options for improvement, it is important to be aware that the space-heating demand of the zones with roof windows may vary considerably depending on the floor plan of the house and the exchange of heat and air between zones. The 1½-storey house generally represents a case with high utilisation of solar gains. Higher utilisation of solar gains than in Paper 5 could be found for south-oriented roof windows in this house if the interaction between storeys is limited, while the storeys themselves are more mixed. In contrast, lower utilisation of solar gains than in Paper 3 could be found if the roof windows were inserted in a one-storey house with considerable separation between zones.

6.6 Research question 6 (Q6)

This section discusses the research question, Q6: *Can improved roof-window frame constructions and glazing U-values lower than current standard levels make it possible to build nearly zero-energy houses in a more cost-effective way?*

The answer to this research question is presumably 'yes'.

Paper 5 showed the following examples of reduced insulation costs in the houses per m^2 improved sloped (Case A) or horizontal (Case B) roof window:

- EUR 170 in Case B for thermal improvements in the glazing (#C). The energy savings at building level were 0.5 kWh/m^2. A similar scope for investment would be expected in Case A.
- EUR 200 in Case A and EUR 600 in Case B for improvements in frame and junctions (#B). The energy savings at building level were 1.7–1.8 kWh/m^2 for the two houses.
- EUR 950 in Case B for a simple combined improvement (#D), where the addition of a 3-pane glazing at the bottom of the light well considerably reduced heat losses through glazing, frame and junctions, all at once. The energy savings at building level were 3.5 kWh/m^2.

The final scope for investment due to the savings above will depend on the lifetime of the products. The windows as a whole may, for example, have to be replaced once and the glazing components twice during a period corresponding to the lifetime of insulation (40–60 years). In comparison with the roof window products that are best standard practice today, users would then be able to pay:

- EUR 50–60 more per m^2 window with improved glazing (#C).
- EUR 100–300 more per m^2 window with improved frame and junctions (#B).
- At least EUR 320 more per m^2 window with the 3-pane glazing added in the light well (#D).

It will be up to the manufacturers to determine the prices at which these improvements can be made available. The scope for investment in the improved glazing (#C), for example, seems likely to match based on estimates from glazing prices, but there may be issues related to how the glazing is built into the frame which need to be addressed by the producers. However, given the large scope for investment in a relatively simple improvement like #D, it is very likely that improved roof windows can be made available at prices that will make it cheaper to build nearly zero-energy houses.

Chapter 7

Conclusions

This chapter concludes on the sub-hypotheses SH1–SH6 and on the main hypothesis, and provides recommendations and suggestions for future work.

7.1 Conclusions on the sub-hypotheses

7.1.1 Sub-hypothesis 1 (SH1)

Sub-hypothesis SH1 was: *The space-heating demand of nearly zero-energy houses can be represented by a few key parameters.*

This sub-hypothesis is true.

The space-heating demand in nearly-zero energy houses can be represented by a few key parameters, most importantly the window parameters and the specific heat losses in constructions. However, since the utilisation of solar gains in these buildings depends on the heating needs of the space, it is not sufficient to study the effect of the window parameters on their own. The effect of changes in the overall space-heating demand of the room or house considered on the window parameters has to be taken into account as well.

7.1.2 Sub-hypothesis 2 (SH2)

Sub-hypothesis SH2 was: *Improvements in the energy performance of façade windows can be identified by studying the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort for individual spaces.*

This sub-hypothesis is true.

The glazing diagram introduced in Paper 2 made it possible to study the effect of various parameters within a solution space defined by targets for daylighting and thermal comfort. Façade windows with light transmittances of 40–70% could provide sufficient daylighting without overheating as long as they were located in rooms with a reasonable layout for daylighting and some solar-control coating was used on glazing oriented south, east and west.

7.1.3 Sub-hypothesis 3 (SH3)

Sub-hypothesis SH3 was: *Improved roof-window frame constructions and glazing U-values lower than current standard levels can increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces.*

This sub-hypothesis is true.

Assuming a maximum venting rate of 4 h^{-1} in Rome and 3 h^{-1} in Copenhagen, roof windows could provide sufficient daylighting without overheating with any choice of light transmittance in both climates provided appropriate solar-control coating is used on south-oriented and horizontal glazing.

Improved roof-window frame constructions and glazing U-values lower than current standard levels made it possible to achieve nearly zero-energy consumption with a wider range of options within the solution space for daylighting and thermal comfort, and with a wider use of rooms with sloped roof windows oriented north. They also reduced the impact of window size on space heating. In Copenhagen, such improvements are strongly recommended to achieve adequate flexibility in building design, while in Rome this was not critical.

7.1.4 Sub-hypothesis 4 (SH4)

Sub-hypothesis SH4 was: *Dynamic solar shading can make room for more daylighting without overheating, but cannot reduce energy use for space heating.*

The first part of this sub-hypothesis is clearly true for both climates, while the second part is true for Copenhagen and false for Rome.

The investigation described in Paper 4 showed that the more flexible solution space with dynamic shading than without made it possible to either increase daylighting by 750–1000 h or reduce the number of hours with operative temperatures exceeding the comfort limit as defined by the Adaptive Thermal Comfort (ATC) model by 40–50 h. In both climates, dynamic shading also made it possible to achieve the same daylighting and thermal comfort as without dynamic shading with less space heating.

However, as an option for reducing the optimum energy use for space heating in the loft room, dynamic shading showed limited potential. The larger windows allowed for by dynamic shading generally increased space-heating demand and, although considerably higher g-values could be used without overheating with dynamic shading than without, the potential for utilising this flexibility in practice was limited by the maximum g-values achievable for the double and triple glazing considered.

In Rome, dynamic shading could potentially reduce space-heating demand with better windows, but in Copenhagen this would require improvements in the windows to beyond the levels that are state of the art today.

7.1.5 Sub-hypothesis 5 (SH5)

Sub-hypothesis SH5 was: *The relative importance of roof-window parameters found at room level holds true at building level.*

This sub-hypothesis is both true and false.

Nothing indicates that the effect of parameters found at room level does not hold true for the type of houses the rooms are intended to represent. However, comparison of results for the sloped roof windows in Copenhagen studied in Papers 3 and 5 showed that differences in the floor plan between houses with the same overall energy use can considerably affect the space-heating demand of the zones with roof windows. This does not change the conclusions with regard to the roof-window thermal properties needed for adequate flexibility, but it does change the relative effect of the roof-window parameters to an extent that might affect the saving potential of the improvements.

7.1.6 Sub-hypothesis 6 (SH6)

Sub-hypothesis SH6 was: *Improved roof-window frame constructions and glazing U-values lower than current standard levels would make it possible to build nearly zero-energy houses in a more cost-effective way.*

This sub-hypothesis is presumably true.

Since it is up to the manufacturers to determine the prices at which various types of improvements can be made available, this hypothesis could not be tested in a way that leads to clear conclusions. However, the case study on two large single-family houses in Paper 5 showed examples of savings in insulation costs due to the installation of various types of improved roof windows that would allow users to pay EUR 50–320 more per m^2 improved roof window than for the current best standard-practice roof windows.

If the improvements can be made available at prices within these scopes for investment identified, this would make it cheaper to build nearly zero-energy houses. For some of the examples this is very likely.

7.2 Conclusion on the main hypothesis (MH)

The main hypothesis tested in this research was:

The current best standard-practice roof windows can be improved in a way that makes the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces easier and more cost-effective.

Based on the evaluation of the sub-hypotheses, it can be concluded that the main hypothesis is probably true for Copenhagen.

Improved roof-window frame constructions and glazing U-values lower than current standard levels would increase flexibility in the design of nearly zero-energy houses with sufficient daylighting and thermal comfort in all spaces. Moreover, examples of the scope for investment in improved roof windows were identified by studying the savings in insulation costs from specific roof-window improvements for two large single-family houses with typical floor plans. Some of these showed a considerable potential for making improved roof windows available at prices that are within the scope for investment. Provided such improvements can be made available, nearly zero-energy houses with sufficient daylighting and thermal comfort throughout could be realised in a more cost-effective way as well.

7.3 Recommendations and future work

Roof-window frames and junctions in Copenhagen showed a large potential for improvement that manufacturers are strongly recommended to consider. Moreover, a scope for investment of EUR 320 per m^2 improved roof window was identified for a relatively simple improvement in the horizontal roof windows, where the addition of 3-pane glazing at the bottom of the light well considerably reduced heat losses through glazing, frame and junctions all at once. This option for improvement is already being further investigated. More modest potentials for thermal improvements were identified in the glazed part alone due to the reductions in transmittance of light and solar energy that come with lower U-values, but the improvements in the glazed part studied in the present research were just examples using well-known double and triple glazing. Experts may come up with better options by which U-values can be further reduced with less reduction in light transmittance and g-value. For every 1 kWh/m^2 saved at building level due to improvements in the roof windows, it was found that insulation costs in the two houses would be reduced by EUR 1914 (Case A) and EUR 3665 (Case B). These amounts might be lower or greater, but presumably they are on the conservative side given that the houses studied were very compact with optimal building components and most of the floor area facing south.

Paper 5 contains detailed information about glazing dimensions, scaling factors needed to maintain sufficient daylighting, etc. This should make it possible to estimate the energy savings and scope for investment for various roof-window improvements in the two houses based on Figure 5.5.1 and the cost of saving 1 kWh/m^2 by using more insulation for the reference scenario. As discussed in the paper, this can be done with good accuracy for small improvements. For large improvements, it can lead to conservative estimates of the energy savings due to the way increased window size increases space heating less the better the window is. Furthermore, estimates of the scope for investment using simplified methods (Section 3.3.1) can be very misleading for large improvements and should be used with extreme caution.

From the two houses with sloped (Case A) and horizontal (Case B) roof windows, it was found as a more general guideline that improvements involving the glazed part led to savings in space-heating demand if the total reduction in the U-value of the window as projected onto the glazed part (see the definition of U_g' in Section 5.5.1 and in Tables 5.5.2–5.5.3) was at least:

- 4.3 times larger than the decrease in g-value (Case A)
- 7.7 times larger than the decrease in g-value (Case B)

These relationships take into account the effect of the increase in glazing size due to the reduction in light transmittance (LT) by assuming that LT will decrease by twice as much as the g-value. This would typically apply for glazing with close to optimal solar-control coating (see Figure 5.5.1).

The relationships above are based on the utilisation of solar gains found in two nearly zero-energy houses where zones with roof windows consumed about 17 kWh/m^2 (Case A) and 11 kWh/m^2 (Case B) for space heating. This utilisation could be lower or higher in other houses with the same overall space-heating demand, depending on the floor plan and the interaction between zones. However, since the effect of increasing the g-value decreased with space-heating demand, while the effect of increasing the window size increased with space-heating demand, the relationships themselves tended to be rather resistant towards changes in space-heating demand. Moreover, analyses made in connection with Paper 3 indicated that the relative effect of the U-value and g-value followed the solution space for daylighting and thermal comfort quite closely, but varied in magnitude depending on the insulation level of the room and the distance to the thermal comfort limit. In future work, it is recommended that the relative effect of the parameters within the solution space in rooms with various insulation levels should be looked into more systematically. This could reveal information which might be useful to further simplify the problem and provide more generally applicable guidelines for improvements. Alternatively, such guidelines might be defined for a range of space-heating demands representative of rooms with roof windows in various types of nearly zero-energy houses.

This research has shown that sufficient daylighting and thermal comfort can be met in any house designed with a reasonable layout for daylighting, without the use of more advanced means than well-dimensioned windows for daylighting and appropriate solar-control coating on horizontal and south/east/west-oriented glazing. Further research may be needed on maximum venting rates, acceptable daylighting and the effect of various user patterns on thermal comfort to verify the robustness of these findings. If they can be considered acceptable, however, nearly zero-energy houses with sufficient daylighting and thermal comfort throughout can be designed by means of very simple guidelines, such as the information in Table 4.4. The daylight criteria tested against thermal comfort in this research may also be used as an input to future debates on reasonable daylighting requirements.

Although the use of higher g-values can reduce space heating, examples in this research have demonstrated how optimal solar-control coating will always be a better option for daylighting and thermal comfort, even in combination with dynamic solar shading. Given the challenge of balancing daylighting and thermal comfort, it is therefore recommended that future window development should focus less on maximising solar gains and more on bringing the thermal properties of windows to a level where users are free to choose the best option for daylighting and thermal comfort.

Bibliography

Acosta, I., Navarro, J. and Sendra, J. J. (2013a). Daylighting design with lightscoop skylights: Towards an optimization of shape under overcast sky conditions. *Energy and Buildings*, *60*, 232–238.

Acosta, I., Navarro, J. and Sendra, J. J. (2013b). Towards an analysis of the performance of lightwell skylights under overcast sky conditions. *Energy and Buildings*, *64*, 10–16.

Acosta, I., Navarro, J. and Sendra, J. J. (2015). Towards an analysis of the performance of monitor skylights under overcast sky conditions. *Energy and Buildings*, *88*, 248–261.

Acosta, I., Navarro, J., Sendra, J. J. and Esquivias, P. (2012). Daylighting design with lightscoop skylights: Towards an optimization of proportion and spacing under overcast sky conditions. *Energy and Buildings*, *49*, 394–401.

Active House Alliance (2013). Active House – The specifications for residential buildings. 2nd ed. Brussels, Belgium. Available at: `http://www.activehouse.info/about/about-active-house/specifications/`.

Active House Alliance (2015). Active House – The guidelines: Comfort, Energy, Environment. Brussels, Belgium. Available at: `http://www.activehouse.info/about/about-active-house/guidelines/`.

Aggerholm, S. O. (2013). Cost-optimal levels of minimum energy performance requirements in the Danish Building Regulations. Danish Building Research Institute, Aalborg University, Copenhagen, Denmark. ISBN 978-87-92739-48-3.

Albatici, R. and Passerini, F. (2011). Bioclimatic design of buildings considering heating requirements in Italian climatic conditions. A simplified approach. *Building and Environment*, *46*(8), 1624–1631.

Ali Ahmed, A. A. E.-M. M. (2012). Using simulation for studying the influence of vertical shading devices on the thermal performance of residential buildings (Case study: New Assiut City). *Ain Shams Engineering Journal*, *3*(2), 163–174.

Appelfeld, D., McNeil, A. and Svendsen, S. (2012). An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems. *Energy and Buildings*, *50*, 166–176.

Apte, J. S., Arasteh, D. K. and Huang, Y. J. (2003). Future Advanced Windows for Zero-Energy Homes. *ASHRAE Transactions*, *109*(2), 871–882. Lawrence Berkeley National Laboratory Report LBNL-51913.

Arasteh, D. K., Goudey, H., Kohler, C., Huang, J. and Mitchell, R. (2007). Performance Criteria for Residential Zero Energy Windows. *ASHRAE Transactions*, *113*(1), 176–185. Lawrence Berkeley National Laboratory Report LBNL-59190.

Arasteh, D. K., Johnson, R. and Selkowitz, S. E. (1985). The Effects of Skylight Parameters on Daylighting Energy Savings. Lawrence Berkeley Laboratory Report LBL-17456.

Arasteh, D. K., Johnson, R., Selkowitz, S. E. and Sullivan, R. (1985). Energy Performance and Savings Potentials with Skylights. *ASHRAE Transactions*, *91*(1), 154–179. Lawrence Berkeley Laboratory Report LBL-17457.

Arasteh, D. K., Kohler, C. and Griffith, B. (2009). Modeling Windows in Energy Plus with Simple Performance Indices. Lawrence Berkeley National Laboratory Report LBNL-2804E.

Atzeri, A., Cappelletti, F. and Gasparella, A. (2014). Internal versus external shading devices performance in office buildings. *Energy Procedia*, *45*, 463–472.

Beltran, L. O., Lee, E. S., Papamichael, K. M. and Selkowitz, S. E. (1994). The design and evaluation of three advanced daylighting systems: Light shelves, light pipes and skylights. In *Proceedings of Solar 94, Golden Opportunities for Solar Prosperity*, 25-30 June, San Jose, California. Lawrence Berkeley Laboratory Report LBL-34458.

Bülow-Hübe, H. (2001). *Energy-efficient window systems. Effects on energy use and daylight in buildings.* Doctoral dissertation, Department of Construction and Architecture, Lund University, Sweden.

BR, Danish Transport and Construction Agency (2014). Danish Building Regulations 2010 Version 31.12.2014 (in Danish). Available at: `http://bygningsreglementet.dk/br10_05/0/42`.

BR, Danish Transport and Construction Agency (2016). Danish Building Regulations 2015 Version 01.07.2016 (in Danish). Accessed 20.08.2016 at: `http://bygningsreglementet.dk/br15_01/0/42`.

BR, Danish Transport and Construction Agency (2017). Bilag 6: Bygningers energiforbrug (in Danish). (Supplement to the Danish Building Regulations 2015). Accessed 11.01.2017 at: `http://bygningsreglementet.dk/br15_01_id5175/0/42`.

Brunsgaard, C., Knudstrup, M.-A. and Heiselberg, P. (2012). Occupant experience of everyday life in some of the first passive houses in Denmark. *Housing, Theory and Society*, *29*(3), 223–254.

Carlucci, S., Cattarin, G., Causone, F. and Pagliano, L. (2015). Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II). *Energy and Buildings*, *104*, 378–394.

CEN (2007). European standard EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

Danish Energy Agency (2016). Low-energy classes (in Danish). Accessed 20.08.2016 at: `http://www.ens.dk/forbrug-besparelser/byggeriets-energiforbrug/lavenergiklasser`.

Danish Ministry of Climate, Energy and Building (2011). Our future energy. The Danish Government, Copenhagen. Accessed 27.04.2017 at: `https://stateofgreen.com/files/download/387`. ISBN 978-87-7844-915-3.

David, M., Donn, M., Garde, F. and Lenoir, A. (2011). Assessment of the thermal and visual efficiency of solar shades. *Building and Environment*, *46*(7), 1489–1496.

DAYSIM (2016). Advanced daylight simulation software.
Accessed 21.08.2016 at: `http://daysim.ning.com/`.

DeForest, N., Shehabi, A., O'Donnell, J., Garcia, G., Greenblatt, J., Lee, E. S., Selkowitz, S. and Milliron, D. J. (2015). United States energy and CO2 savings potential from deployment of near-infrared electrochromic window glazings. *Building and Environment*, *89*, 107–117.

Du, J. (2014). Window systems and energy performance in one-family houses: Size and shading effects. In *Proceedings of the Building Simulation and Optimization Conference*, pp. 209–216, 23-24 June, London.

Du, J., Hellström, B. and Dubois, M.-C. (2013). Assessing the impact of window systems on energy performance in houses: An integrated analysis. In *Proceedings of the 12th European Lighting Conference LuxEuropa2013*, pp. 259–264, 17-19 September, Poland.

Du, J., Hellström, B. and Dubois, M.-C. (2014). Daylighting utilization in the window energy balance metric: Development of a holistic method for early design decisions. Technical Report, Department of Architecture and the Built Environment, Lund University, Sweden.

Dubois, M.-C., Grau, K., Traberg-Borup, S. and Johnsen, K. (2003). By og Byg Dokumentation 047: Impact of three window configurations on daylight conditions. Simulations with Radiance. Danish Building and Urban Research, Hørsholm, Denmark. ISBN 87-563-1183-4.

EnergyPlus (2013). Weather Data Download – Rome 162420 (IWEC). Accessed 12.03.2013 at: `https://energyplus.net/weather-location/europe_wmo_region_6/ITA//ITA_Rome.162420_IWEC`.

EU, European Union (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union, 18/06/2010, Strasbourg, France.

Firląg, S., Yazdanian, M., Curcija, C., Kohler, C., Vidanovic, S., Hart, R. and Czarnecki, S. (2015). Control algorithms for dynamic windows for residential buildings. *Energy and Buildings*, *109*, 157–173.

Foldbjerg, P. and Asmussen, T. (2013). Using ventilative cooling and solar shading to achieve good thermal environment in a Danish Active House. *The REHVA European HVAC Journal*, *50*(3), 36–42.

Freewan, A. A. Y. (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*, *102*, 14–30.

Gasparella, A., Pernigotto, G., Cappelletti, F., Romagnoni, P. and Baggio, P. (2011). Analysis and modelling of window and glazing systems energy performance for a well insulated residential building. *Energy and Buildings*, *43*(4), 1030–1037.

Goia, F. and Cascone, Y. (2014). The impact of an ideal dynamic building envelope on the energy performance of low energy office buildings. *Energy Procedia*, *58*, 185–192.

Grynning, S., Time, B. and Matusiak, B. (2014). Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces. *Solar Energy*, *107*, 182–194.

Gugliermetti, F. and Bisegna, F. (2003). Visual and energy management of electrochromic windows in Mediterranean climate. *Building and Environment*, *38*(3), 479–492.

Gugliermetti, F. and Bisegna, F. (2007). Saving energy in residential buildings: The use of fully reversible windows. *Energy*, *32*(7), 1235–1247.

Hansen, S. and Vanhoutteghem, L. (2012). A method for economic optimization of energy performance and indoor environment in the design of sustainable buildings. In *Proceedings of the 5th International Building Physics Conference*, 28-31 May, Kyoto, Japan.

Huang, Y., Niu, J.-L. and Chung, T.-M. (2014). Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. *Applied Energy*, *134*, 215–228.

IES (2013). IES Lighting Measurements (LM) 83-12. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Illuminating Engineering Society, New York. ISBN: 978-0-87995-272-3.

Ihm, P., Park, L., Krarti, M. and Seo, D. (2012). Impact of window selection on the energy performance of residential buildings in South Korea. *Energy Policy*, *44*, 1–9.

Inanici, M. N. and Demirbilek, F. N. (2000). Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. *Building and Environment*, *35*(1), 41–52.

Jaber, S. and Ajib, S. (2011). Thermal and economic windows design for different climate zones. *Energy and Buildings*, *43*(11), 3208–3215.

Jensen, J. M. and Lund, H. (1995). Design Reference Year, DRY – et nyt dansk reference år (in Danish). Technical Report lfv-281, Technical University of Denmark, Kgs. Lyngby, Denmark.

Johnsen, K., Dubois, M.-C. and Grau, K. (2006). SBi 2006:08: Assessment of daylight quality in simple rooms. Impact of three window configurations on daylight conditions, Phase 2. Danish Building Research Institute, Hørsholm, Denmark. ISBN 87-563-1270-9.

Johnson, R., Sullivan, R., Selkowitz, S. E., Nozaki, S., Conner, C. and Arasteh, D. K. (1984). Glazing energy performance and design optimization with daylighting. *Energy and Buildings*, *6*(4), 305–317.

Karabay, H. and Arıcı, M. (2012). Multiple pane window applications in various climatic regions of Turkey. *Energy and Buildings*, *45*, 67–71.

Karlsson, J., Karlsson, B. and Roos, A. (2000). Control strategies and energy saving potentials for variable transmittance windows versus static windows. In *Proceedings of Eurosun*, 19-22 June, Copenhagen, Denmark.

Kim, G., Lim, H. S., Lim, T. S., Schaefer, L. and Kim, J. T. (2012). Comparative advantage of an exterior shading device in thermal performance for residential buildings. *Energy and Buildings*, *46*, 105–111.

Klems, J. H. (2001). Net energy performance measurements on electrochromic skylights. *Energy and Buildings*, *33*(2), 93–102.

Kragh, J., Laustsen, J. B. and Svendsen, S. (2008). Proposal for Energy Rating System of windows in EU. Report R-201, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.

Larsen, T. S. and Jensen, R. L. (2009). Measurements of energy performance and indoor environmental quality in 10 Danish passive houses: A case study. In *Proceedings of the 9th International Conference & Exhibition of Healthy Buildings*, 13-17 September, Syracuse, New York.

Lee, E. S., DiBartolomeo, D. L. and Selkowitz, S. E. (1998). Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. *Energy and Buildings*, *29*(1), 47–63.

Lee, E. S. and Tavil, A. (2007). Energy and visual comfort performance of electrochromic windows with overhangs. *Building and Environment*, *42*(6), 2439–2449.

Li, D. H. W., Lam, T. N. T. and Cheung, K. L. (2009). Energy and cost studies of semi-transparent photovoltaic skylight. *Energy Conversion and Management*, *50*(8), 1981–1990.

Maccari, A. and Zinzi, M. (2001). Simplified algorithms for the Italian energy rating scheme for fenestration in residential buildings. *Solar Energy*, *69, Supplement 6*, 75–92.

Manz, H. and Menti, U.-P. (2012). Energy performance of glazings in European climates. *Renewable Energy*, *37*(1), 226–232.

Mardaljevic, J. (2006). Examples of Climate-Based Daylight Modelling. Paper No. 67. In *Proceedings of the CIBSE National Conference 2006: Engineering the Future*, 21-22 March, London.

Mardaljevic, J. (2008). Climate-Based Daylight Analysis for Residential Buildings. Impact of various window configurations, external obstructions, orientations and location on useful daylight illuminance.

Mardaljevic, J., Andersen, M., Roy, N. and Christoffersen, J. (2012). Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building. Technical Report, VELUX A/S, Hørsholm, Denmark.

Mardaljevic, J. and Christoffersen, J. (2013). A roadmap for upgrading national/EU standards for daylight in buildings. In *Proceedings of the CIE Centenary Conference*, 15-16 April, Paris.

Mardaljevic, J. and Christoffersen, J. (2017). 'Climate connectivity' in the daylight factor basis of building standards. *Building and Environment*, *113*, 200–209.

Marsh, R., Larsen, V. G. and Kragh, M. (2010). Housing and energy in Denmark: Past, present, and future challenges. *Building Research & Information*, *38*(1), 92–106.

Mavrogianni, A., Davies, M., Taylor, J., Chalabi, Z., Biddulph, P., Oikonomou, E., Das, P. and Jones, B. (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. *Building and Environment*, *78*, 183–198.

McCluney, R. (1984a). SKYMODE – Annual energy performance simulation model for skylights. *Energy and Buildings*, *6*(4), 353–360.

McCluney, R. (1984b). SKYSIZE – A simple procedure for sizing skylights based upon statistical illumination performance. *Energy and Buildings*, *6*(3), 213–219.

Meier, A. (1983a). The cost of conserved energy as an investment statistic. *Heating, Piping and Air Conditioning*, *55*(9), 73–77.

Meier, A. (1983b). What is the cost to you of conserved energy? *Harvard Business Review*, *61*(1), 36–37.

Motuziene, V. and Juodis, E. S. (2010). Simulation based complex energy assessment of office building fenestration. *Journal of Civil Engineering and Management*, *16*(3), 345–351.

Nielsen, M. V., Svendsen, S. and Jensen, L. B. (2011). Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. *Solar Energy*, *85*(5), 757–768.

Nielsen, T. R., Duer, K. and Svendsen, S. (2000). Energy performance of glazings and windows. *Solar Energy*, *69, Supplement 6*, 137–143.

O'Brian, W., Athienitis, A. and Kesik, T. (2011). Thermal zoning and interzonal airflow in the design and simulation of solar houses: A sensitivity analysis. *Journal of Building Performance Simulation*, *4*(3), 239–256.

O'Connor, J., Lee, E. S., Rubinstein, F. M. and Selkowitz, S. E. (1997). Tips for Daylighting with Windows: The Integrated Approach. Lawrence Berkeley National Laboratory Report LBNL-39945.

Persson, M.-L., Roos, A. and Wall, M. (2006). Influence of window size on the energy balance of low energy houses. *Energy and Buildings*, *38*(3), 181–188.

Petersen, S. (2015). Daylight conditions and thermal indoor climate in low-energy homes – the consequence of Danish building code. In *Proceedings of the 7th Passivhus Norden, Sustainable Cities and Buildings*, 20-21 August, Copenhagen, Denmark.

Pilkington (2014). Glasfakta 2015: Et praktisk hjælpemiddel for valg af bygningsglas (in Danish). Pilkington Floatglas AB, Halmstad, Sweden.

Poirazis, H., Blomsterberg, Å. and Wall, M. (2008). Energy simulations for glazed office buildings in Sweden. *Energy and Buildings*, *40*(7), 1161–1170.

Robertson, S. and Thompson, M. (2006). Guidelines for sizing roof windows. *WIT Transactions on The Built Environment*, *86*. ISSN 1743-3509. Accessed 27.04.2017 at: `http://www.witpress.com/elibrary/wit-transactions-on-the-built-environment/86/16363`.

Selkowitz, S. E. and Gabel, M. (1984). LBL Daylighting Nomographs. Lawrence Berkeley Laboratory Report LBL-13534. Accessed 28.04.2017 at: `https://buildings.lbl.gov/sites/all/files/13534.pdf`.

Shen, H., Tzempelikos, A., Atzeri, A. M., Gasparella, A. and Cappelletti, F. (2015). Dynamic commercial façades versus traditional construction: Energy performance and comparative analysis. *Journal of Energy Engineering*, *141*(4).

Singh, R., Lazarus, I. J. and Kishore, V. V. N. (2015). Effect of internal woven roller shade and glazing on the energy and daylighting performances of an office building in the cold climate of Shillong. *Applied Energy*, *159*, 317–333.

Sullivan, R., Beck, F. A., Arasteh, D. K. and Selkowitz, S. E. (1995). Energy Performance of Evacuated Glazings in Residential Buildings. *ASHRAE Transactions*, *102*(2). Lawrence Berkeley Laboratory Report LBL-37130.

Sullivan, R., Lee, E. S., Rubin, M. D. and Selkowitz, S. E. (1996). The energy performance of electrochromic windows in heating-dominated geographic locations. In *Proceedings of the SPIE International Symposium on Optical Materials Technology for Energy Efficiency & Solar Energy Conversion XV*, 16-19 September, Freiburg, Germany. Lawrence Berkeley Laboratory Report LBL-38252.

Sullivan, R. and Selkowitz, S. E. (1985a). Energy Performance Analysis of Fenestration in a Single-Family Residence. *ASHRAE Transactions*, *91*(2). Lawrence Berkeley Laboratory Report LBL-18561.

Sullivan, R. and Selkowitz, S. E. (1985b). Window Performance Analysis in a Single-Family Residence. In *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings III Conference*, 2-5 December, Clearwater Beach, Florida. Lawrence Berkeley Laboratory Report LBL-20079.

Svendsen, S. (2011). Analyse 6. Komponentkrav, konkurrence og eksport – En kortlægning af innovation i byggekomponenter (in Danish). Technical Report, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark.

Treado, S., Gillette, G. and Kusuda, T. (1984). Daylighting with windows, skylights, and clerestories. *Energy and Buildings*, *6*(4), 319–330.

Tsikaloudaki, K., Laskos, K., Theodosiou, T. and Bikas, D. (2015). The energy performance of windows in Mediterranean regions. *Energy and Buildings*, *92*, 180–187.

Tsikaloudaki, K., Theodosiou, T., Laskos, K. and Bikas, D. (2012). Assessing cooling energy performance of windows for residential buildings in the Mediterranean zone. *Energy Conversion and Management*, *64*, 335–343.

Tzempelikos, A. and Shen, H. (2013). Comparative control strategies for roller shades with respect to daylighting and energy performance. *Building and Environment*, *67*, 179–192.

U.S. Department of Energy (2016). EnergyPlus energy simulation software. Accessed 21.08.2016 at: `http://apps1.eere.energy.gov/buildings/energyplus/`.

Vanhoutteghem, L. and Svendsen, S. (2014). Modern insulation requirements change the rules of architectural design in low-energy homes. *Renewable Energy*, *72*, 301–310.

Webb, A. R. (2006). Considerations for lighting in the built environment: Non-visual effects of light. *Energy and Buildings*, *38*(7), 721–727.

Yao, J. and Zhu, N. (2012). Evaluation of indoor thermal environmental, energy and daylighting performance of thermotropic windows. *Building and Environment*, *49*, 283–290.

Yohanis, Y. G. and Norton, B. (2000). A comparison of the analysis of the useful net solar gain for space heating, zone-by-zone and for a whole-building. *Renewable Energy*, *19*(3), 435–442.

Yun, G., Yoon, K. C. and Kim, K. S. (2014). The influence of shading control strategies on the visual comfort and energy demand of office buildings. *Energy and Buildings*, *84*, 70–85.

Zhang, Y. (2009). 'Parallel' EnergyPlus and the development of a parametric analysis tool. In *Proceedings of the IBPSA BS2009*, pp. 1382–1388, 27-30 July, Glasgow, UK.

Zhang, Y. and Korolija, I. (2010). Performing complex parametric simulations with jEPlus. In *Proceedings of the SET2010 – 9th International Conference on Sustainable Energy Technologies*, 24-27 August, Shanghai, China. Accessed 28.04.2017 at: `http://www.jeplus.org/wiki/lib/exe/fetch.php?media=docs:set2010-shanghai-se-102.pdf`.

Appended Papers

Paper 1

"Investigation and description of European buildings that may be representative for 'nearly zero' energy single-family houses in 2020"

G.C.J. Skarning, S. Svendsen and C.A. Hviid

Published in: *Proceedings of the CISBAT Conference, Lausanne, 2013*

Published in Proceedings of the CISBAT Conference, Lausanne, 4-6 September, 2013, pp. 247-252.

INVESTIGATION AND DESCRIPTION OF EUROPEAN BUILDINGS THAT MAY BE REPRESENTATIVE FOR "NEARLY ZERO" ENERGY SINGLE FAMILY HOUSES IN 2020

G.C.J.Skarning[1]; S.Svendsen[1]; C.A.Hviid[1]

1: Department of Civil Engineering, Technical University of Denmark, Section of Building Physics and Services, DK-2800 Kgs. Lyngby.

ABSTRACT

As part of European energy politics and strategies for reduction of fossil fuels all new buildings should have a "nearly zero" energy consumption in 2020. This creates a strong need for research in cost-effective technologies and solutions that will contribute to the fulfilment of the ambitious energy reductions without compromising desirable daylight conditions and indoor climate. This development requires knowledge about the demands and possibilities of the low energy building mass of the future. An important basis for the research within this field will therefore be the establishment of a set of reference parameters that can be expected to be representative for the behaviour of the "nearly zero" energy building of 2020 in different European climatic zones. This paper provides an overview of how single family houses with a very low energy demand for space heating and cooling can be approached by rational and conventional means in three different European climates: Rome, Bratislava and Copenhagen. Special attention is paid to the role of windows and their contribution to solar gains in these well-insulated buildings of the future. By a neutral treatment of the window configurations towards different orientations, where the windows in all rooms are dimensioned based on the diffuse daylight access at the specific location, it is shown that an equal window distribution will allow fulfilment of an ambitious energy target, while simultaneously enabling a balanced daylight access across the building and a comfortable indoor climate. Furthermore, the analyses indicate that the ability of these well-insulated buildings to utilise solar gains is highly restricted, even at the location of Copenhagen. Window panes with a solar control coating seem to be an appropriate protection against overheating for all three locations.

Keywords: Building parameters, European climates, energy, daylight, windows, solar gain.

INTRODUCTION

The establishment of cost-optimal levels for energy requirements is a task requiring several considerations, spanning from future energy prices and discount rates to local possibilities. According to the guidelines accompanying the Commission Delegated Regulation (EU) No 244/2012 on the energy performance of buildings, it is the responsibility of the member states to set minimum energy performance requirements for their buildings with a view to achieving cost-optimal levels. This paper aims at providing an example of how buildings with a low energy demand for space heating and cooling can be achieved based on a selected target. The analyses are the first step towards a more detailed study on how windows with optimal properties for the energy frame in 2020 can be developed. For this reason, special attention is paid to the link between the building behaviour and the windows. The overall building performance must be transparent to the effect of orientation, window configuration and room distribution, and it must be possible to trace both the heating and cooling demand back to a specific room with a specific orientation and window fraction. Furthermore, daylight conditions, energy demand and thermal environment must be evaluated at room level and the behaviour of rooms with different orientation must be comparable.

The daylight access is considered an unquestionable aspect of the building performance, thus all solutions are created in accordance with an ambitious daylight target. The analyses will lead to a suggestion on low energy solutions for each location, followed by parameter variations on how these solutions are affected by different glazing properties.

METHOD

In accordance with the criteria above, the symmetrical building set up in Figure 1 is chosen.

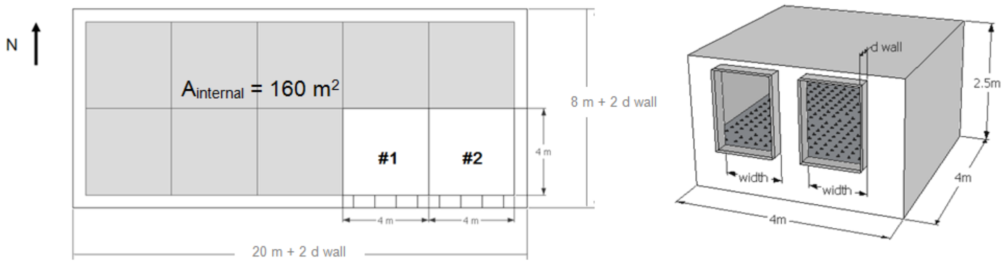


Figure 1: Building set up. The building is composed by equal quadratic rooms and oriented South-North for neutral treatment of room composition, window distribution and orientation.

A building with internal floor area of 160 m^2 is composed by 10 equal quadratic room modules with the internal dimensions 4 x 4 x 2.5 m. All modules are side-lit by two windows and the variable dimensions are the wall thickness and window width. These will depend on the amount of insulation and window size needed in order to reach the selected targets for both energy and daylight. The building is oriented South-North and the relevant room types are evaluated separately. As the transmission area in rooms located at a building corner (#2) is significantly larger than in the rooms positioned in the middle (#1), all results will be derived from the individual area weighted performance of these two room types. The heating and cooling demands are given for the two building halves facing South and North respectively and for the building in total.

Locations and climate

The locations Rome, Bratislava and Copenhagen are selected for the study, representing three different latitudes and two different longitudes at the continental part of Europe (Figure 2).

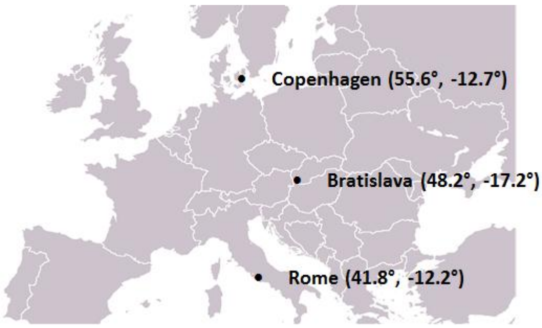


Figure 2: The three different locations.

Both a room's heating and cooling demand and its access to daylight are climate-dependent. The access to light and solar gains decreases nearly linearly from Rome in South to Copenhagen in North, while Bratislava is positioned in between. Moreover, Rome and Copenhagen represent coastal climates with rather small temperature differences between summer and winter, whereas Bratislava, which is located in the central parts of Europe, experiences large temperature variations from -20°C in winter to 30°C in summer [1].

Windows dimensioned according to the availability of diffuse light at the location

In order to create building solutions with comparable daylight conditions across the different climates, the windows are dimensioned for an occurrence of 300 lux in 50 % of the light hours at 50 % of the work plane under the diffuse daylight availability at the given location. Target and methodology are selected with reference to the on-going discussions on how European daylight standards can be upgraded in a way that approaches climate-based daylight modelling (CBDM), which delivers daylight predictions under realistic sun and sky conditions [2]. For the purpose of these comparative studies, a simplified methodology from these proposals is chosen, where the effect of the sun and its position is neglected. Under the assumption that the diffuse light access at the locations follows the same graduation in brightness as the CIE overcast sky model, a target daylight factor (DF_{target}) can be derived for the different locations based on the median daylight level required indoors and the diffuse median illuminance available outdoors ($E_{median\ diffuse}$):

$$DF_{TARGET} = \frac{300\ lux}{E_{MEDIAN\ DIFFUSE}} \qquad (1)$$

The DF target values for the different locations and the window fractions required in order to meet the selected target are given in Table 1, along with an illustration of the spatial daylight distribution in the rooms. All calculations are performed with Daysim for comparability with fully climate-based approaches. A diffuse reflectance of 70 % is assumed for walls and ceiling and a reflectance of 30 % for floors.

Heating and cooling demand based on EN ISO 13790

For comparison across the countries, all buildings are optimised with off-set in the same energy target. After subtraction of energy needed for ventilation fans, pumps and domestic hot water, the target for the annual space heating and cooling demand is set to 13 kWh/m^2.

The heating and cooling demands are calculated according to the hourly method with simplified input-parameters described in EN ISO 13790. The method simplifies the heat transfer between the external and internal environment, but distinguishes between the internal air temperature and the mean radiant temperature. This enables its use in principle for thermal comfort checks [3]. Standard set-points of 20°C and 26°C are used for heating and cooling respectively. Venting is controlled based on a set-point of 23°C and solar shadings are modelled by means of a simplified shading factor. Movable solar shadings are activated when the irradiation on the external window surface exceeds 300 W/m^2. The calculations are performed with the program WinDesign, developed at the Technical University of Denmark. Climate files are collected from the U.S. Department of Energy's homepage [1].

General building specifications and assumptions

Mechanical ventilation with heat recovery and the constant air change rate of 0.6 h^{-1} is applied all year in order to ensure an indoor air quality in accordance with EN 15251. A high heat recovery efficiency of 90 % with bypass during the cooling season favours comfortable supply temperatures and keeps the ventilation losses to a minimum. As a simplification the infiltration rate is set to 0. Natural ventilation with a maximum venting rate of 3 h^{-1} is used in order to reduce the overheating and cooling demands. The internal gains from people, equipment and lighting are 5 W/m^2 and the thermal capacity 260,000 J/K m^2. In general the building envelope holds a high quality and all connections are constructed for minimum heat losses (see footnote in Table 1).

RESULTS

The building parameters that are directly related to the fulfilment of the energy and daylight targets are now restricted to *insulation thickness*, *window size* and *glazing properties*. Reasonable values for these parameters are selected through iterations between window optimisation for daylight, insulation thicknesses required for energy and reasonable choices of glazing properties. The suggested set of building parameters are given in Table 1 and Figure 3 illustrates the heating and cooling demand of the solutions.

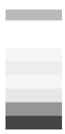
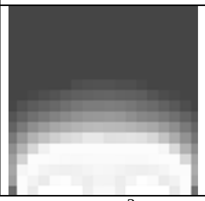
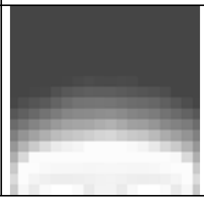
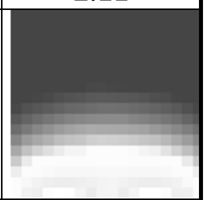
Variable building parameters		**Unit**	**Rome**	**Bratislava**	**Copenhagen**
Insulation*	Insulation thickness	mm	125	300	250
	Wall thickness	m	0.325	0.500	0.450
	U-value, wall	W/m^2 K	0.20	0.10	0.12
	U-value, roof/floor	W/m^2 K	0.14/ 0.11	0.06/ 0.05	0.07/ 0.06
Window size	Fraction of internal floor area	%	24	30	32
Glazing	Type	-	2-layer	3-layer	3-layer
	U-value	W/m^2 K	1.0	0.5	0.5
	g-value	-	0.27	0.27	0.27
	TL	%	50	50	50
Daylight	DF target	%	1.56	1.84	2.11
	Spatial distribution of daylight target. Dark area: DA $300_{diffuse}$ < 50 %				
*) Additional properties of the building envelope; U_{frame} = 1.34 W/m^2 K (width = 0.057 m, ψ = 0.33 W/m K), $\psi_{window/wall}$ = 0.01 W/m K and $\psi_{foundation}$ = 0.13 W/m K. Insulation in roof/floor is the double amount as in walls.					

Table 1: Suggested values for the climate-dependent building parameters.

Triple glazings are needed in Bratislava and Copenhagen, whereas double glazings are found sufficient in Rome. Although Bratislava is located in a southern climate relative to Copenhagen, the large variations between summer and winter force the insulation thickness to exceed Danish levels. Glazings with a solar control coating and a g-value of 0.27 are selected as a cheap mean for control of overheating. In Copenhagen, where there are no traditions for mechanical cooling, the decision is based on whether the comfort limits can be met without additional solar shadings or not. This was found possible with the selected g-value of 0.27.

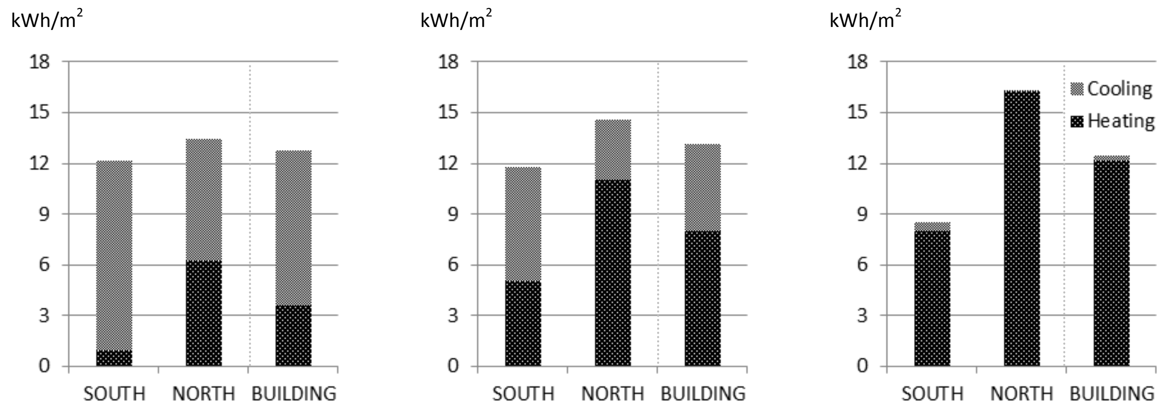


Figure 3: Energy demand of the solutions. From left: Rome, Bratislava and Copenhagen.

Figure 4 and Figure 5 show parameter variations on the window glazing properties, with the building solutions suggested above indicated with the grey line labelled “ref”.

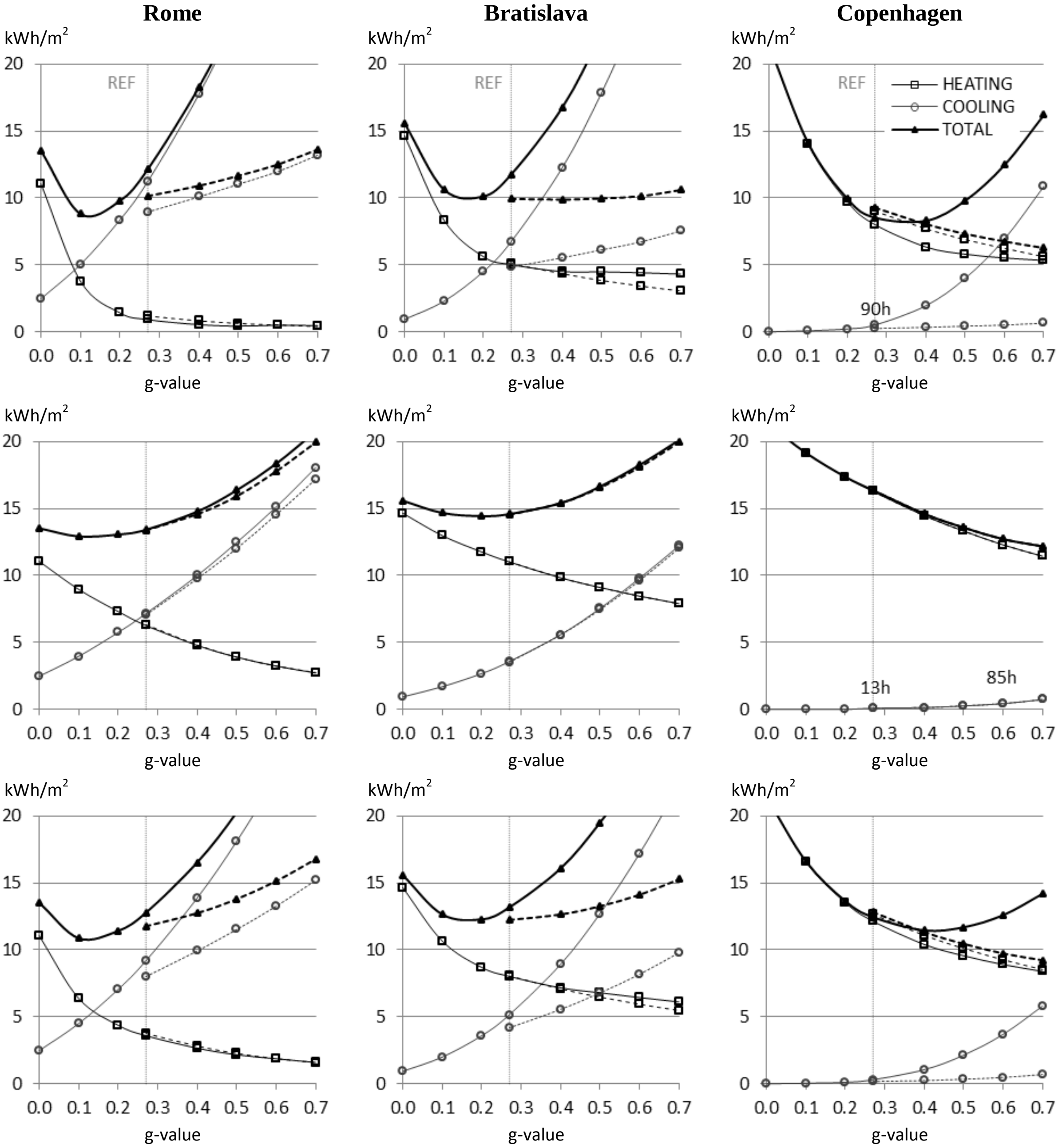


Figure 4: Heating and cooling demand as a function of g-value. From top: South, North and the building in total. Dashed lines represent the addition of movable solar shadings with shading coefficient 0.2 when activated. Equivalent overheating is indicated for Copenhagen.

DISCUSSION

In Rome and Bratislava the optimal g-values are found in the range of 0.1 - 0.2 for both orientations. This indicates that even the diffuse solar gains in rooms facing North contributes to more overheating than they reduce the need for space heating. The g-value’s effect on the heating demand stagnates around this level in rooms facing South. Furthermore, the positive effect of low g-values seems to override the potential energy saving by choosing smaller windows with higher light transmittances. Smaller windows would however be favourable if the solar loads could be kept down by movable solar shadings or other means. For this purpose a potential may be found in the use of fully climate-based methods for daylight optimisation. This may allow further reductions of window area in the rooms that are most exposed to direct and indirect sun. In Copenhagen the optimal g-value is found at 0.4 for the building in total. This contradicts the current practice in Denmark, where high g-values are favoured by the energy rating system for windows. Furthermore, the flexible range of this optimum may open new development possibilities for the related glazing parameters. In a room oriented towards the North, higher g-values are still favourable and movable solar shadings may in general enable energy savings in Copenhagen. For further conclusions, the cooling demands must be verified by a reliable program. Moreover, the robustness of the findings to changes in internal gains and other building parameters must be investigated.

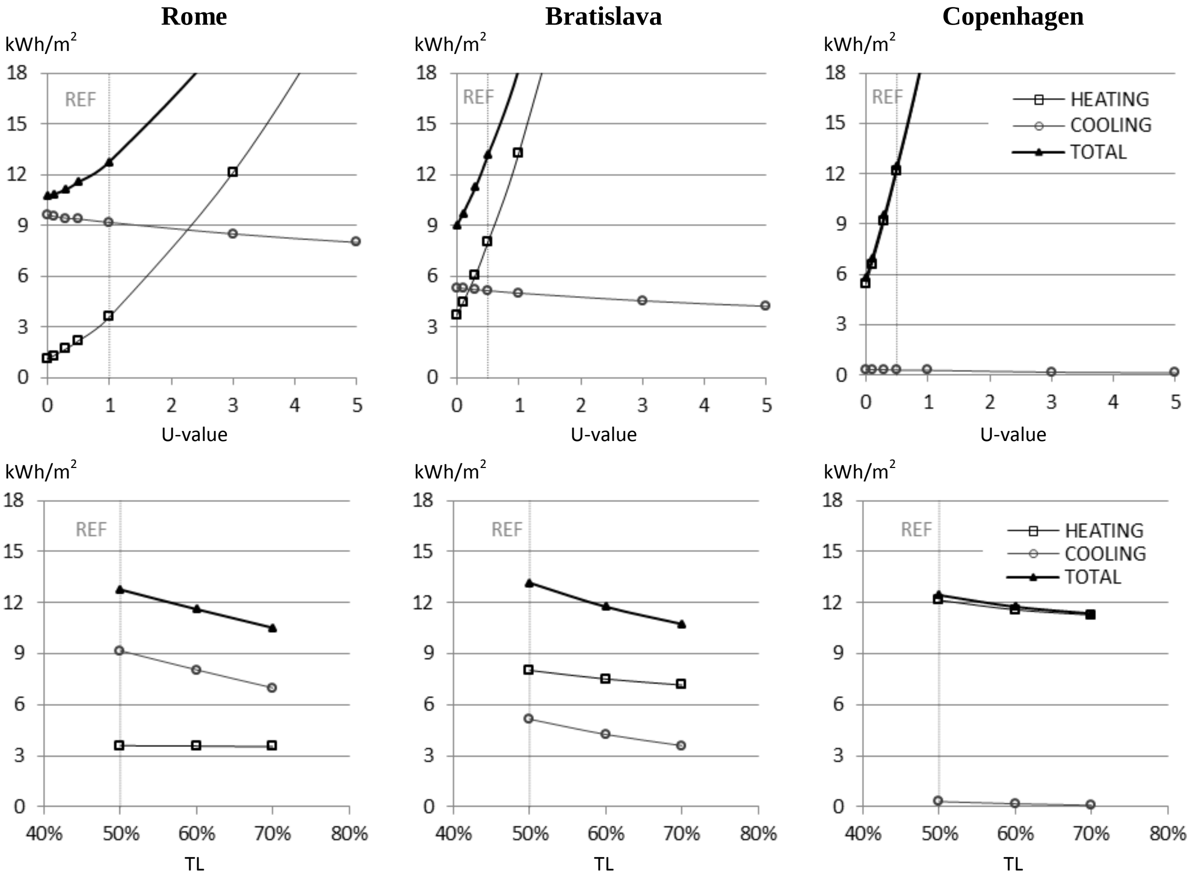


Figure 5: Building heating and cooling demand as a function of glazing U-value (top) and light transmittance (bottom), given that the window fraction is adjusted for sufficient daylight.

ACKNOWLEDGEMENTS

The work is funded by VELUX A/S and the author gratefully thanks colleagues at VELUX for fruitful discussions and their important contributions to the investigations.

REFERENCES

1. The U. S. Department of Energy: EnergyPlus Energy Simulation Software. Weather Data. *http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm*, accessed 2013.
2. Mardaljevic, J. and Christoffersen, J.: A roadmap for upgrading national/EU standards for daylight in buildings. Proc. of the CIE conference, Paris, 2013.
3. EN ISO 13790 : Thermal performance of buildings. Calculation of energy use for space heating and cooling.

Paper 2

"Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses"

L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid and S. Svendsen

Published in: *Energy & Buildings 102 (2015) 149-156*

Energy and Buildings 102 (2015) 149–156

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses

Lies Vanhoutteghem *, Gunnlaug Cecilie Jensen Skarning, Christian Anker Hviid, Svend Svendsen

Technical University of Denmark, Department of Civil Engineering, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 29 November 2013
Received in revised form 30 April 2015
Accepted 11 May 2015
Available online 19 May 2015

Keywords:
Nearly zero-energy houses
Fenestration
Thermal indoor environment
Daylighting
Window size
Glazing properties
Geometry factors

ABSTRACT

Appropriate window solutions are decisive for the design of 'nearly zero-energy' buildings with healthy and comfortable indoor environment. This paper focuses on the relationship between size, orientation and glazing properties of façade windows for different side-lit room geometries in Danish 'nearly zero-energy' houses. The effect of these parameters on space heating demand, daylighting and thermal environment is evaluated by means of EnergyPlus and DAYSIM and presented in charts illustrating how combinations of design parameters with minimum space heating demand can be selected within a solution space defined by targets for daylighting and thermal comfort. In contrast with existing guidelines, the results show an upper limit for energy savings and utilisation of solar gains in south-oriented rooms. Instead, low *U*-values are needed in both north- and south oriented rooms before large window areas lead to reductions in space heating demand. Furthermore, windows in south-oriented rooms have to be carefully designed to prevent overheating. Design options for prevention of overheating, however, correspond well with options for low space heating demand. Glazings with solar control coating are therefore obvious alternatives to dynamic solar shadings. Regarding room geometry, deep or narrow south-oriented rooms show difficulties in reaching sufficient daylight levels without overheating.

1. Introduction

As part of European energy strategy and policy for reducing the use of fossil fuels, all new buildings are required to have a 'nearly zero' energy consumption in 2020 [1]. This creates a strong need for research in cost-effective technology and solutions that will help meet these ambitious energy reductions without compromising on daylight conditions and indoor climate. It is well-known that windows have a considerable effect on both energy consumption and indoor environment. For example, where large windows allow for more daylight in a space, they might also result in visual discomfort and excessive heat gains or losses which affect the energy needed for heating or cooling and the thermal indoor environment. So it is important to find a balance between daylight availability, thermal comfort and energy consumption if we are to achieve both the goal of a 'nearly zero' energy consumption and buildings with a healthy and comfortable indoor environment. There have been many studies on window design with regard to energy consumption for heating, cooling and lighting in office buildings. Studies carried out by Susorova et al. [2] and Ghisi and Tinker [3] focused on the effect of room geometry, window size and orientation on energy use for heating, cooling and lighting for office buildings in various climate zones. A study by Lee et al. [4] examined the effect of window-to-wall ratios, orientation, *U*-value, *g*-value and visual transmittance to find optimal window designs for office buildings in 5 typical climate zones in Asia. Similarly, Motuziene and Juodis [5] investigated the effect of window-to-wall ratios, window orientation and glazing type on the total building energy consumption for an office building in the cool climate zone of Lithuania, while a study conducted by Ko [6], explored ways of optimising daylighting and energy savings by performing simulations to find the best combination of window area and glazing properties for office buildings in six different climates in the U.S.

Due to the less predictable usage and occupancy in residential buildings, the link between energy consumption, thermal environment and daylighting is less obvious in residential buildings than in commercial buildings. Furthermore, while in office buildings most energy is used for cooling and lighting, in residential buildings there has been a historical focus on reducing the energy needed for heating. These might be reasons why, the topic of the integrated evaluation of window design and its combined effect on heating, cooling and lighting has been less explored in residential buildings.

* Corresponding author. Present address: Danish Building Research Institute, Aalborg University Copenhagen, A.C. Meyers Vænge 15, DK-2450 Copenhagen, Denmark. Tel.: +45 9940 2347.
E-mail address: lva@sbi.aau.dk (L. Vanhoutteghem).

http://dx.doi.org/10.1016/j.enbuild.2015.05.018
0378-7788/© 2015 Elsevier B.V. All rights reserved.

Table 1
Room dimensions and width-to-depth ratio for each room geometry.

	2:1		1.5:1		1:1		1:1.5		1:2	
	W (m)	*D* (m)	*W* (m)	*D* (m)	*W* (m)	*D* (m)	*W* (m)	*D* (m)	*W* (m)	*D* (m)
Large rooms	8	4	6	4			4	6	4	8
Base case					4	4				
Small rooms	5.3	2.7	4	2.7			2.7	4	2.7	5.3

A number of studies on the topic of lighting in residential buildings have evaluated daylight availability and the potential for savings in artificial lighting with various geometries and window sizes [7–9]. Studies on reducing the heating and cooling demand in residential buildings have considered the influence of window orientation, size and glazing type and suggested that south-facing window size is important for reducing heating demand [10–13]. However, a study by Persson et al. [14] on the performance of passive houses in Sweden has shown that window size is not that important any more for the reduction of heating demand. In well-insulated residential buildings, the focus should be on reducing the risk of overheating.

Recently, there has been renewed attention on the thermal indoor environment and potential non-visual effects of daylighting in residential buildings [15] as part of a movement towards sustainable buildings with a focus on user well-being [16]. 'Active houses' [16] should be designed, for example, so that they allow for optimal daylighting and attractive views to the outside while ensuring a good thermal indoor environment and low energy consumption without having negative impact on the environment. Following the Active house specifications [17], a house called 'Home for life' was designed and constructed in Denmark as part of the Model Home 2020 project, which has the aim of developing climate-neutral buildings with a high level of livability [18]. The house has a window-to-floor ratio of 40% to achieve an average daylight factor of 5%. This is about twice the window-to-floor area usually used in single-family houses. Even so, the overall thermal indoor environment is good, due to the special attention given to solar control using dynamic solar shading and ventilative cooling by natural stack ventilation through the use of roof windows [19]. Another example is the design of a Danish passive house [20] in which the glazing area was selected to provide a daylight factor of 2% all the way to the back of primary rooms. Here, however, there were problems with overheating because no solar control of any kind was provided [21].

We believe that the establishment of cost-effective and successful window solutions in 'nearly zero-energy' buildings requires more knowledge about the link between various window design parameters and their combined effect on energy consumption, daylighting and thermal indoor environment for rooms with different geometries. In this paper we wish to contribute to this knowledge by studying the effect of glazing-to-floor ratio, orientation, and glazing properties such as *U*-value, *g*-value and light transmittance in side-lit rooms with different geometries representing Danish 'nearly zero-energy' single-family houses. The results are presented in terms of diagrams, exemplifying an approach by which window solutions with minimum space heating demand can be chosen within a solution space defined by targets for daylighting and thermal comfort.

2. Methodology

2.1. Simulation process and model description

Daylighting was computed independently from energy consumption and thermal indoor environment. For the calculation of energy consumption and thermal environment, the building simulation tool EnergyPlus (version 7.2) [22] was used in combination with the tool jEPlus 1.4 [23,24], which is a parametric shell program designed for use with EnergyPlus. EnergyPlus has been widely validated and is an acknowledged simulation tool that uses the heat balance model to predict thermal performance in buildings. EnergyPlus allows for hourly calculation of space heating demand and operative temperatures based on detailed treatment of solar radiation. Analyses with regard to daylighting were carried out using the RADIANCE-based daylighting analysis tool DAYSIM (version 3.1) [25]. The targets and evaluation criteria used throughout this paper are further explained in Section 2.2.

2.1.1. Room geometry

To study the relationships between window size, orientation, *U*-value, *g*-value and visual light transmittance, the investigations were made at room level. This made it possible to investigate how window size, orientation and geometry affect the performance in a transparent way. A total of 9 different room dimensions with varying width-to-depth ratios were used, see Table 1.

Rooms were modelled with ceiling, floor and one façade exposed to the outside climate to represent rooms in typical Danish single-family houses, which are characterised by their rectangular shape and one-storey floor plan. Room height was set to 2.5 m and a wall thickness of 0.5 m was used. No external obstructions were taken into account.

2.1.2. Building specifications

Construction and building system properties for the various room geometries were selected to comply with future requirements for the annual energy consumption in 'nearly zero-energy' houses in Denmark [26]. These requirements are in form of a target energy frame, stating a maximum yearly heating demand (see Section 2.2). Table 2 contains input data on construction, building system properties, and internal loads for the simulation model. The heating set-point and design values for internal gains were chosen in accordance with standard practice in Denmark [27]. Heating power to achieve the heating set point was assumed infinite by using the ideal loads air system in EnergyPlus [28]. Mechanical ventilation was set to 0.6 h^{-1} while infiltration was set to 0.05 h^{-1} for

Table 2
Input values defining the thermal simulation model with respect to construction properties, and system and internal loads.

Construction properties	
U-value wall[1]	0.10 W/m^2 K
U-value roof[1]	0.08 W/m^2 K
U-value floor[1]	0.09 W/m^2 K
System and internal loads	
Heating set point	20 °C
Venting set point	23 °C
Infiltration rate	0.05 h^{-1}
Venting rate (maximum)	3 h^{-1}
Mechanical ventilation rate	0.6 h^{-1}
Efficiency of heat recovery	0.9
Internal gains from people	1.5 W/m^2
Internal gains from equipment and lighting	3.5 W/m^2

[1] Includes linear heat losses.

Table 3
Variables used for parameter analyses.

Parameter	Variable
Orientation	N/S
Glazing-to-floor ratio[1] (%)	10/15/20[2]/25[3]/30/35
Glazing *U*-value (W/m^2 K)	0.3/0.5/0.7/0.9
Glazing *g*-value (−)	0.1/0.2/0.3/0.4/0.5/0.6/0.7
Light transmittance (−)	0.3/0.4/0.5/0.6/0.7

[1] Based on internal floor area.
[2] Glazing-to-floor ratios greater than 20% were not investigated for the room with geometry 4 m × 8 m.
[3] Glazing-to-floor ratios greater than 25% were not investigated for the room with geometry 4 m × 6 m.

the whole year. Natural ventilation through opening of windows, referred to as venting, was set to 3 h^{-1} outside the heating season. This corresponds to the maximum air flow rate possible for single-sided natural ventilation by automated opening of windows [27]. To ensure a good thermal indoor environment, solar protection should be integrated early in the design [21,29], in addition to venting. Recent findings [30,31] have indicated that the importance of a high *g*-value for reducing space heating demand for south-oriented rooms in 'nearly zero-energy' buildings is limited even in the Danish climate, which makes the cost-efficiency of dynamic shading solutions debatable. Therefore, in this research work, we considered *g*-value to reflect the use of permanent solar shadings (glazing with solar control coating) instead of using dynamic shading solutions.

For daylight calculations, a diffuse reflectance of 70% was assumed for walls and ceiling and a reflectance of 30% for floors.

2.1.3. Parameter variations

Glazing-to-floor ratio, orientation, and glazing properties such as *U*-value, *g*-value and visual transmittance were varied as indicated in Table 3 for each of the room geometries. The window frame considered for the investigations has a thermal transmittance of 0.9 W/m^2 K and a width of 5 cm, which was kept the same for all investigations.

For the different glazing-to-floor ratios, the glazing height was kept constant at 1.5 m while the glazing width was varied. Windows were placed as high in the façade as possible for optimal diffuse daylight access. Depending on the room geometry, rooms were side-lit by 1 to 4 windows. A consistent relationship between the off-set from side walls and off-set between windows was used to ensure an optimal daylight distribution. Fig. 1 illustrates the variation in glazing-to-floor ratio for a 4 m × 4 m room.

2.1.4. Weather data

The study considered rooms with different geometries for single-family houses located in Copenhagen, Denmark. This location in the northern part of continental Europe (latitude 55.6° and longitude −12.7°) represents a temperate coastal climate with rather small temperature differences between summer and winter and low to medium access to daylight and solar radiation on an annual basis. Weather data from the Danish Reference Year [32] was used for the calculations.

2.2. Evaluation criteria

The link between various window design parameters and their combined effect on energy, daylighting and thermal indoor environment can be assessed using different evaluation criteria. However, several dilemmas exist in finding suitable evaluation criteria [33–35]. Where different evaluation criteria are used to assess a single aspect of the same problem, this can lead to multiple valid solutions. For example, energy consumption can be quantified by evaluation of consumption for both heating, cooling, lighting, ventilation energy etc. Since the tradition for mechanical space cooling is limited in Denmark due to the climate, energy consumption was evaluated based on the space heating demand alone in kW h/m^2 per year. This annual space heating demand was calculated based on the hourly simulation results for space heating demand from EnergyPlus. The parameter variations for glazing-to-floor ratio and different window properties indicated in Table 3 will give a variation in results. Combinations of parameters that result in an annual space heating demand of 13 kW h/m^2 or less can be considered suitable for reaching the targeted energy frame as defined in the Danish Building Code.

The thermal indoor environment was considered a boundary condition restricting possible window solutions. Different criteria and methods can be used for evaluation of thermal indoor environment. The thermal adaptive comfort method is currently being used as a new way to evaluate thermal indoor environment, but could benefit from further research [36]. We evaluated thermal indoor environment based on the thermal comfort requirements in the Danish building code for nearly-zero residential buildings [26]. The requirements state that to have a comfortable indoor environment without overheating, no more than 100 hours where the operative temperature exceeds 26 °C should be allowed. The total number of hours with operative temperatures above 26 °C was found based on evaluation of hourly results from EnergyPlus. If the number of hours with operative temperatures above 26 °C exceeds 100 hours per year, this is referred to as overheating.

The methodology and targets for the evaluation of daylighting in residential buildings are less clearly defined. For offices, a daylight factor of 2% is required in the working plane, but for nearly-zero energy residential buildings, the Danish building code only requires a minimum glazing-to-floor ratio of 15% in primary rooms when side-lit windows with a light transmittance of 0.75 are used [36]. If the light transmittance is lower, the glazing-to-floor ratio should be increased proportionally. Moreover, electricity consumption for artificial lighting is not included in the target for primary energy consumption in residential buildings. For these reasons and the less obvious usage and occupancy in residential buildings, daylighting was evaluated as an independent performance parameter, rather than expressed in terms of a reduction in energy used for artificial lighting. Provided that rooms are designed for a high daylight performance with regard to comfort and health, we considered the potential electricity savings for artificial lighting a question of control systems and the usage of the building, rather than of window design. Furthermore, it was not the aim to investigate visual discomfort. Instead, it was assumed that users can draw curtains to control glare, or adapt to glare by moving around in the space. In the

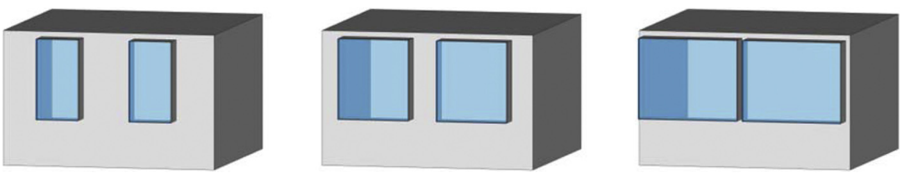


Fig. 1. Illustration of glazing-to-floor-ratio for a 4 m × 4 m room. From left to right: Glazing-to-floor ratio of 15%, 25% and 35%.

following, we present a target and methodology for the evaluation of daylighting.

2.2.1. Target and methodology for evaluation of daylighting

We selected target and methodology for the evaluation of daylighting with reference to the on-going discussions on how European daylight standards can be upgraded in a way that approaches climate-based daylight modelling (CBDM), which provides daylight predictions under realistic sun and sky conditions based on available weather data [37]. Over the last decade, research in the field of daylighting has discussed the shortcomings of the daylight factor method [37,38]. The daylight factor is calculated under standard CIE overcast sky conditions, so variations in daylight over time for different climates, locations and building orientations are not considered. Furthermore, the use of daylight factor requirements can sometimes result in conflicts between visual and thermal comfort requirements [39]. However, the daylight factor method is still used in guidelines and standards [17,26,40]. Moreover, the use of CBDM requires expert knowledge or expert simulation tools, while the daylight factor method uses existing tools and requires less computation power.

As a transition between the current practice of using the daylight factor method and the use of CBDM, Mardaljevic and Christoffersen [41] suggested the use of a slight modification to the daylight factor method that creates connectivity to the diffuse daylight access at a specific location, referred to in this paper as a climate-dependent approach. On the assumption that the diffuse daylight access follows the same graduation in brightness as the CIE overcast sky model, a target daylight factor (DF_{target}, %) for various locations can be derived based on the target for median illuminance indoors (E_{target}, lx) and the median diffuse illuminance available outdoors ($E_{median,\,diffuse}$, lx) during daylight hours:

$$DF_{target} = \frac{E_{target}}{E_{median,\,diffuse}}$$

with $E_{median,\,diffuse}$ calculated as the cumulative availability of diffuse illuminance from standardized climate files during daylight hours and with daylight hours defined as the hours from sunrise to sunset (solar altitude $\geq 0°$).

When E_{target} is set to 300 lx, which is considered adequate by most building users, the target daylight factor in Copenhagen is calculated to 2.11% [41]. In this study, the final daylight access of the different room geometries was evaluated as the achievement of 300 lx (or DF_{target} 2.11%) across 50% of the work plane. Since the median of the outdoor diffuse illuminance ($E_{median,\,diffuse}$) is used for the calculation of this achievement, this means that, for half of the daylight hours in a year, half of the surface of the horizontal work plane receives 300 lx or more. In contrast to the use of an average daylight factor, this provides information about the spatial distribution of daylight in the different rooms and ensures that daylighting in the different rooms is not only evaluated based on their predicted occupied period, due to the choice of the daylight hours as the evaluation period. However, this is not a fully climate-based approach and cannot be used as a measure for equal daylight availability for south- and north-oriented rooms over time under realistic sky conditions. On the other hand, because the climate-dependent methodology is based on overcast sky conditions, it does ensure that a sensor-point that reaches the target daylight factor (DF target) will receive a minimum of 300 lx in 50% of the daylight hours on an annual basis. The spatial distribution of the daylight target was evaluated for a grid of sensor points with a mask width of 0.2 m distributed over the surface of the horizontal work plane at 0.85 m above floor level.

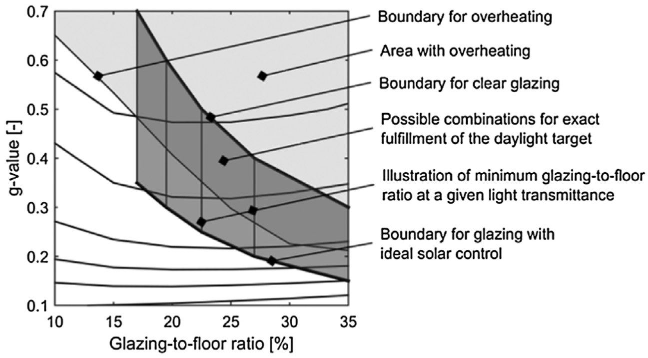


Fig. 2. Conceptual illustration of contour plot of space heating demand for various g-values and glazing-to-floor ratios, indicating boundaries for overheating and daylighting.

2.3. Coupling between energy consumption and targets for daylighting and thermal comfort

To obtain useful information about the relationship between the various window design parameters and their effect on space heating demand, thermal indoor environment and daylighting, the results for each of these parameters are presented in the same graphical illustration. For each room geometry investigated, space heating demand was plotted in a contour plot as a function of glazing-to-floor ratio and g-value for north and south orientations separately. The combinations of glazing-to-floor ratio and g-value at which indoor temperatures were above 26 °C for more than 100 hours were plotted as a boundary indicating overheating on the contour plot, see Fig. 2.

The boundary for daylighting at different combinations of glazing-to-floor ratio and g-value was established through the relationship between g-value and light transmittance. This relationship, also known as the ‘daylighting efficiency’ of glazing, varies for different glazing products. However, due to physical limitations, light transmittance is at maximum twice the solar transmittance (daylight efficiency 2). This characterizes glazings with an ideal solar control and serves as a lower limit to illustrate daylight availability. The upper limit was set to represent a clear glazing that is advantageous in situations where a large amount of solar gain is beneficial. We chose to define this boundary as the case where the light transmittance equals the solar transmittance (daylight efficiency 1). The minimum glazing-to-floor ratio that is needed for the different light transmittances to fulfil the daylight target can then be illustrated as vertical lines ranging from a solar glazing with a g-value as low as possible, to a clear glazing with g-value as high as possible. Existing products on the market can be found within this range of different daylight efficiencies. However, to fulfil targets for both daylighting and thermal comfort, only products above the limit for daylighting reached with ideal solar control glazing and below the boundary for overheating should be selected. This solution space can then also be used to choose a window design with the lowest space heating demand that fulfils targets for both daylighting and thermal comfort.

3. Results

3.1. Effect of U-value, g-value and glazing-to-floor ratio

Before discussing the full solution space defined by targets for daylighting and thermal comfort, we look into the effect of glazing U-value, g-value and glazing-to-floor ratio on space heating demand. Results are illustrated in Fig. 3 for the base case, a room with dimensions of 4 m by 4 m, but also apply to the other

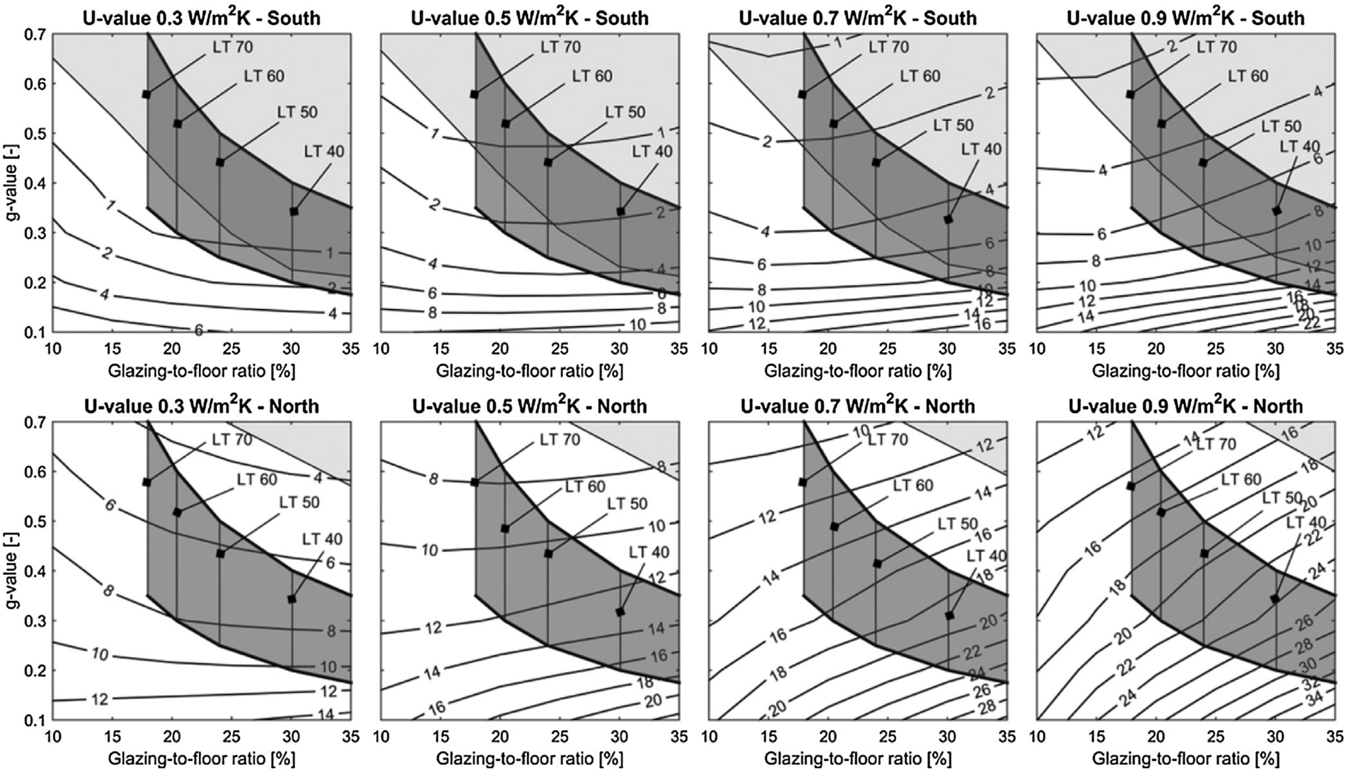


Fig. 3. Contour plot of space heating demand for various *g*-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for a room with dimensions of 4 m × 4 m and for different glazing *U*-values.

geometries. For the variables considered, the results show that *U*-value has only marginal effect on thermal comfort. On the contrary, space heating demand, as well as the best choice of glazing-to-floor ratio and *g*-value to reduce space heating demand, is to a high degree determined by glazing *U*-value. Orientation is also important in this connection.

Where in general it can be observed that sufficient access to solar gains can reduce space heating demand significantly, it was found in south-oriented rooms that there is an upper limit for energy savings and the amount of solar gains that can be utilized. When studying the *g*-value, Fig. 3 shows that the ability to utilise solar gains varies across *U*-value, but for *U*-values of 0.5 W/m^2 K and below, a relatively pronounced stagnation in the energy savings achieved by increasing the *g*-value can be observed at *g*-values as low as 0.3–0.4. For the *U*-values 0.7–0.9 W/m^2 K, the stagnation occurs at slightly higher *g*-values, but for *g*-values above 0.5, increasing the *g*-value further will reduce space heating demand by less than 1 kW h/m^2. In north-oriented rooms, where space heating demand is higher, the benefits of high *g*-values for reducing space heating demand decrease with lower *U*-values and with higher *g*-values, but in general the importance of a high *g*-value remains significant for the whole range of variables investigated.

Considering glazing-to-floor ratio, an optimum glazing-to-floor ratio of approximately 15–20% can be found in both north- and south-oriented rooms. For high glazing *U*-values in south-oriented rooms, larger glazing-to-floor ratios increase space heating demand, while for glazing *U*-values below 0.5 W/m^2 K larger glazing-to-floor ratios can be chosen freely with respect to space heating demand. This indicates that the amount of solar gains that can be utilised in well-insulated buildings can only outweigh the additional heat losses that occur with larger glazing-to-floor ratios when *U*-values are low. These findings are in contrast with existing guidelines and current practice for window design where high *g*-values and large glazing-to-floor ratios in south-oriented rooms are recommended.

Similar tendencies can be found for the lower *U*-values in north-oriented rooms. This means that it could be possible to achieve a window design with a neutral (or even positive) energy balance also in north-oriented rooms when *U*-values are sufficiently low.

3.2. Solution space and daylighting for different geometries

We now discuss the solution space and daylight achievement for rooms with different geometries. As an example, Fig. 4 illustrates the solution space for two different room geometries with width-to-depth ratios of 1:1.5 and 1.5:1 for a glazing *U*-value of 0.5 W/m^2 K. The same trends can, however, also be extended to geometries with width-to-depth ratios of 1:2 and 2:1 and the other glazing *U*-values investigated in this paper.

Results show that the solution space for which both thermal comfort and daylight conditions are satisfactory is considerably larger for north-oriented rooms than for south-oriented rooms. Furthermore, comparison of results for the different geometries shows that small deep geometries are preferable from the perspective of space heating demand in both north- and south-oriented rooms, while wide rooms with a shallow depth are preferable for daylighting. To achieve the same daylight access in deep rooms as in wide rooms with the same floor area, a larger glazing-to-floor ratio is generally needed. This will result in increased space heating demand, especially when high *U*-values are used, which could outweigh some of the benefits of deep rooms in terms of energy consumption.

With regard to room geometry, it was also found that, in deep or very narrow south-oriented rooms, either daylighting or the thermal comfort is compromised when a window design is chosen. To achieve the daylight target without overheating in other south-oriented rooms, windows have to be dimensioned for nearly exact fulfillment of the daylight target, and solar-coated products with close to ideal daylight efficiency are needed. This is also illustrated in Fig. 5 indicates the glazing-to-floor ratios that can be used in

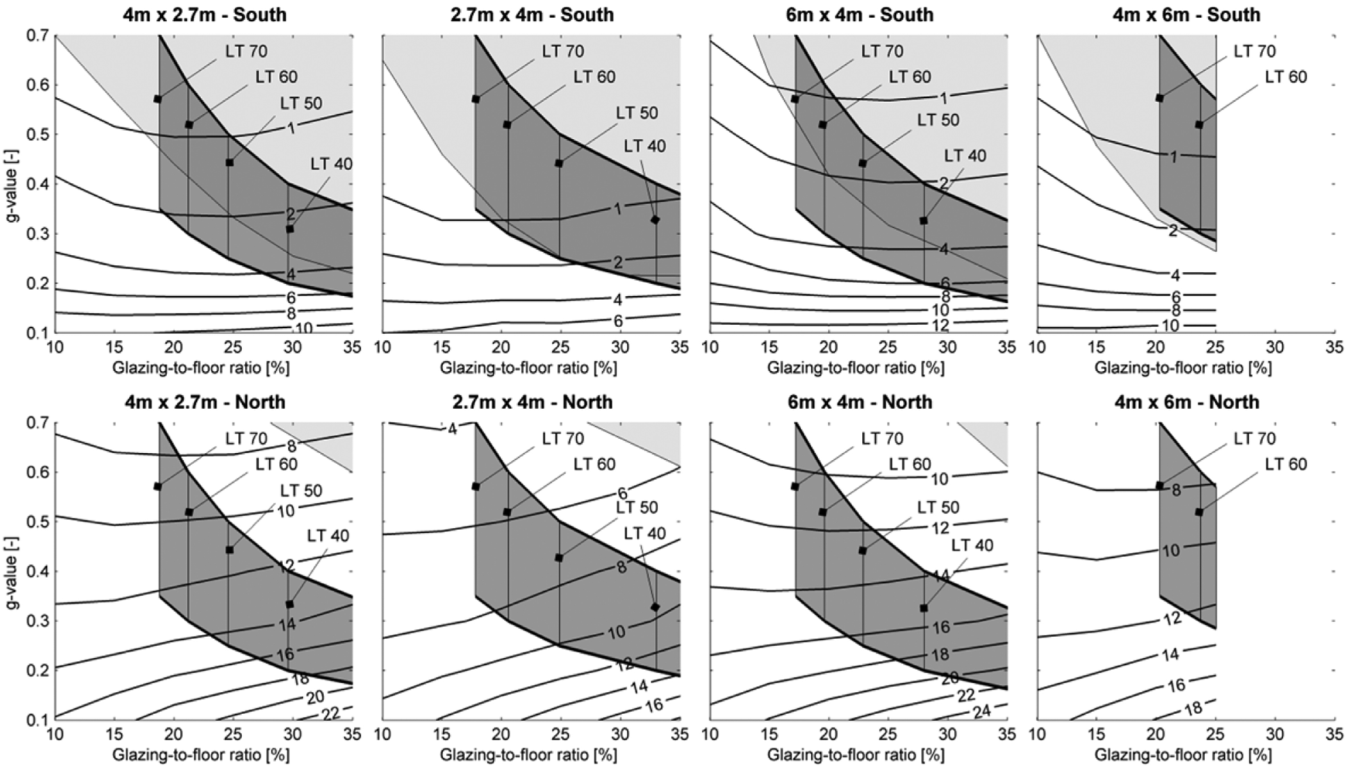


Fig. 4. Contour plot of space heating demand for various *g*-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for two different room sizes with a width-to-depth ratio of 1:1.5 and 1.5:1 and for a glazing *U*-value of 0.5 W/m^2 K.

combination with clear glazing or glazing with ideal solar control (see Section 2.3) without resulting in overheating. The glazing-to-floor ratios needed to achieve the specified daylight target for each light transmittance (0.5–0.7) are also illustrated.

For north-oriented rooms, none of the geometries experience problems with overheating before achieving the daylight target, even when clear glazings are used. However, in deep rooms facing north, for example a room with dimensions of 4 m × 8 m, the target for daylight cannot be met due to the physical limitations of the geometry. When considering the geometries that can achieve the daylight target without overheating, glazing-to-floor ratios of approximately 17–25% are needed to achieve the daylight target for light transmittances of 0.7–0.5 in both north- and south-oriented rooms. This is close to the recommendations in the Danish building code, which states that a glazing-to-floor ratio of 15% is needed for a light transmittance of 0.75 [26].

Fig. 5 also shows that the daylight target in deep and narrow rooms can only be achieved for light transmittances of at least 0.6–0.7, but in general glazing products ranging from high to low light transmittance can be used if they are combined with the right

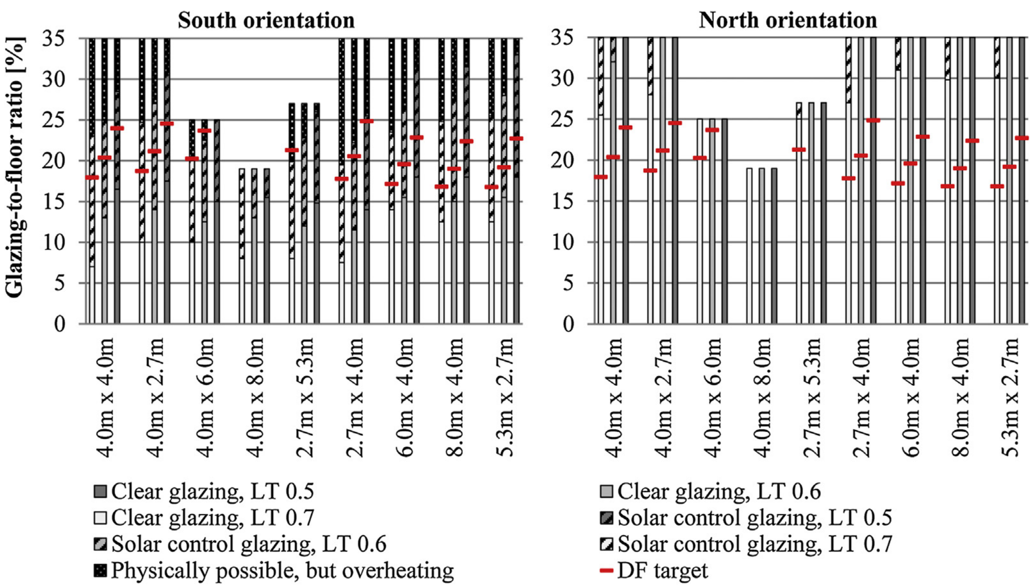


Fig. 5. Indication of glazing-to-floor ratios and glazing types that can be used to achieve the daylight target (DF target) without overheating for light transmittances of 0.7, 0.6 and 0.5 for various room geometries.

glazing-to-floor ratio. However, glazing types with high light transmittances and as high *g*-values as possible generally allow for a lower space heating demand than products with lower light transmittances and as high *g*-values as possible.

The range of available *g*-values in south-oriented rooms is slightly larger for high light transmittances, than for low transmittances. Glazing products with low *U*-values and high light transmittances also provide the best fit between the maximum *g*-values for prevention of overheating and the *g*-values at which the energy savings start to stagnate, see Fig. 4. Furthermore, high light transmittances allow the use of smaller glazing-to-floor ratios for daylighting (within the range of 17–25%). This could be an advantage in cases where less glazing is desirable due to cost and will also allow for the lowest possible space heating demand if high *U*-values are used. In north-oriented rooms, small glazing-to-floor ratios and high light transmittances are also preferable for high glazing *U*-values. At low glazing *U*-values, flexibility in choosing a window design increases and larger glazing-to-floor ratios could be used, provided that clear glazings with high *g*-values are chosen in north-oriented rooms to reduce space heating demand.

4. Discussion

The parametric analyses and the charts illustrating the solution space in this study invite for an open discussion of the link between various design and performance parameters as well as the possibilities and potential conflicts related to façade window design in 'nearly zero-energy' houses. For example, the charts highlight potential design conflicts in deep or narrow south-oriented rooms, because either thermal comfort or daylighting is compromised when only façade windows are used. Conflict situations like this can lead to a discussion on the performance parameters and the chosen targets in the charts, but could also indicate the need for investigations on other design possibilities, e.g. the use of roof windows in deep south-oriented rooms, or alternative solutions such as increased venting (for example using cross ventilation) could be considered. In principle, all the performance parameters and the chosen targets can be tested for sensitivity to e.g. different insulation thicknesses, different user patterns and adaptive models for thermal comfort, different ventilation systems and air change rates, and different daylight targets. The solution space will then also have different characteristics.

In the Danish climate, it was possible to have a window design for certain room geometries fulfilling the targets for daylighting and thermal comfort without the use of mechanical cooling, but with the use of permanent solar shading and with a maximum venting rate of 3 h^{-1}. In this connection, further studies related to other climates and performance parameters should be considered. For example, in warmer climates, where mechanical cooling might be needed to avoid overheating, the value of daylighting compared to the energy used for cooling may give rise to several discussions, such as the relative weight assigned to the performance parameters and targets. It might then also be relevant to consider whether window sizes should be dimensioned based on realistic sun and sky conditions.

The target used for daylight evaluation in our study was chosen to reflect a specific location, but does not take into account realistic sun and sky conditions because it is based on evaluation of the daylight target under a CIE overcast sky. As a result, glazing-to-floor ratios for providing enough daylighting were found to be the same for both north and south-oriented rooms. However, due to prevention of overheating in south-oriented rooms, more flexibility with regard to the choice of window size and geometries was found for north-oriented rooms than for south-oriented rooms. For the two orientations to have comparable daylighting over time under realistic sun and sky conditions either the glazing-to-floor ratio towards the south must be decreased or the glazing-to-floor ratio towards the north must be increased. As the risk of overheating is close to insignificant in north-oriented rooms, it could be argued that slightly larger glazing-to-floor ratios should generally be used here than in south-oriented rooms when low *U*-values are used. In this case, a climate-based approach for the evaluation of daylight may be needed. The use of such an approach might also increase the choice of room geometry. Investigations by Ko [6], taking into account a clear sky and sun at equinox at noon for different locations, showed for example that a lower sun position in winter results in more daylight penetration deeper in a room. However, further studies on visual comfort in south-oriented rooms and the effects of daylighting on human health, comfort and well-being, will be needed to determine how comparable targets for north- and south-oriented rooms can be set in residential buildings. At this stage, the use of a target daylight factor taking into account building location might be considered a valid approach because architects and designers do not always have the knowledge or expert tools to calculate the available daylight using CBDM in the early design phases.

5. Conclusions

The relationships between various façade window parameters (glazing-to-floor ratio, orientation and glazing properties) and how these affect energy consumption, thermal indoor environment and daylighting were studied for different side-lit room geometries representing Danish 'nearly zero-energy' single-family houses. With regard to daylight performance, a target daylight factor taking into account building location was used. Charts illustrating a solution space for space heating demand defined by targets for daylighting and thermal comfort were used to discuss the effect of various window parameters. These charts can also be used to select a window design that is beneficial in terms of all three performance parameters. The main results showed that:

- The use of high *g*-values and large glazing-to-floor ratios in south-oriented rooms to reduce space heating demand is less important than traditionally believed in well-insulated houses. Findings in this paper showed that *g*-values above 0.3–0.4 have limited effect on decreasing the space heating demand. Furthermore, glazing *U*-values between 0.3–0.5 W/m^2 K are needed before the use of very large glazing-to-floor ratios may lead to reductions in space heating demand.
- In order to reach the daylight target without overheating in south-oriented rooms, windows have to be carefully dimensioned on the basis of the daylight target and solar-coated products with close to ideal daylight efficiency are needed. For high light transmittances and low *U*-values, the choice of *g*-value from the perspective of space heating demand corresponds well with the *g*-value for prevention of overheating by use of solar-coated products with close to ideal daylight efficiency. Permanent solar shading solutions, such as solar-coated glazing products with some degree of daylight efficiency, could therefore be used as robust, user-friendly and cost-effective alternatives to dynamic solar shading devices to reduce overheating in south-oriented rooms. Nevertheless, one should keep in mind that some types of solar-coating can give a slight tint to the glass, which might be undesirable.
- In north-oriented rooms, high *g*-values are recommended to reduce space heating demand. As the risk of overheating is small in north-oriented rooms, the combination of *g*-value and glazing-to-floor ratio can be chosen relatively freely to fulfill the target for daylighting. At low *U*-values, this flexibility in north-oriented

rooms also means that a window design with large-glazing-to-floor ratios can be used without having a more negative impact on space heating demand than a design with smaller glazing-to-floor ratios.

- In deep or narrow south-oriented rooms, either thermal comfort or daylighting is compromised with the use of permanent solar shading. Greater flexibility with regard to geometry was found in north-oriented rooms, but this is when the daylight availability for both orientations is evaluated under a standardized overcast sky, without taking orientation or direct sun into account.

Acknowledgements

The authors would like to thank VELUX A/S and the Bjarne Saxhofs Foundation for their financial support for this research.

References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Off. J. Eur. Union L 153 (2010) 21, 18/06/2010, Strasbourg, France.
[2] I. Susorova, M. Tabibzadeh, A. Rahman, H.L. Clack, M. Elnimeiri, The effect of geometry factors on fenestration energy performance and energy savings in office buildings, Energy Build. 57 (2013) 6–13.
[3] E. Ghisi, J.A. Tinker, An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings, Build. Environ. 40 (2005) 51–61.
[4] J.W. Lee, H.J. Jung, J.Y. Park, J.B. Lee, Y. Yoon, Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements, Renewable Energy 50 (2013) 522–531.
[5] V. Motuziene, E.S. Juodis, Simulation based complex energy assessment of office building fenestration, J. Civil Eng. Manage. 16 (3) (2010) 345–351.
[6] D.-H. Ko, Fenestration Guideline for Energy and Daylight Efficiency: Evaluation and Prediction of Performance in Office Buildings, Illinois Institute of Technology, Chicago, IL, USA, 2009 (Doctoral Dissertation).
[7] D.H.W. Li, S.M. Lo, J.C. Lam, R.K.K. Yuen, Daylighting performance in residential buildings, Archit. Sci. Rev. 42 (3) (1999) 213–219.
[8] D.H.W. Li, S.L. Wong, C.L. Tsang, G.H.W. Cheung, A study of the daylighting performance and energy use in heavily obstructed residential buildings via computer simulation techniques, Energy Build. 38 (2006) 1343–1348.
[9] N.H. Wong, A.D. Istiadji, Effect of external shading devices on daylighting penetration in residential buildings, Light. Res. Technol. 36 (4) (2004) 317–333.
[10] M.N. Inanici, F.N. Demirbilek, Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey, Build. Environ. 35 (2000) 41–52.
[11] K. Hassouneh, A. Alshboul, A. Al-Salaymeh, Influence of windows on the energy balance of apartment buildings in Amman, Energy Convers. Manage. 51 (2010) 1583–1591.
[12] A. Gasparella, G. Pernigotto, F. Cappelletti, P. Romagnoni, P. Baggio, Analysis and modelling of window and glazing systems energy performance for a well-insulated residential building, Energy Build. 43 (2011) 1030–1037.
[13] S. Jaber, S. Ajib, Optimum, technical and energy efficiency design of residential building in Mediterranean region, Energy Build. 43 (2011) 1829–1834.
[14] M-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energy Build. 38 (2006) 181–188.
[15] M. Andersen, J. Mardaljevic, S.W. Lockley, A framework for predicting the non-visual effects of daylight—Part I: Photobiology-based model, Light. Res. Technol. 44 (2012) 37–53.
[16] Active House Alliance, Active House—A Vision, 2013, ⟨http://www.activehouse.info/about-active-house/active-house-vision⟩ (accessed 04.08.13).
[17] Active House Alliance, Active House–The Specifications, second ed., Active House Alliance, Brussels, Belgium, 2013.
[18] Model Home 2020. 2013. http://www.velux.com/Sustainable_living/Model_Home_2020 (accessed 04.08.13).
[19] P. Foldbjerg, T. Asmussen, Using ventilative cooling and solar shading to achieve good thermal environment in a Danish Active House, REHVA Eur. HVAC J. 50 (3) (2013) 36–42.
[20] Komforthusene. 2013. ⟨http://komforthusene.dk/⟩ (accessed 04.08.13).
[21] T.S. Larsen, Vurdering af indeklimaet i hidtidigt lavenergibyggeri–med henblik på forbedringer i fremtidens lavenergibyggeri, in: DCE Contract Report No. 100, Aalborg University, 2011 (in Danish).
[22] US Department of Energy, EnergyPlus Energy Simulation Software, 2013, ⟨http://apps1.eere.energy.gov/buildings/energyplus/⟩ (accessed 02.07.13).
[23] Y. Zhang, I. Korolija, Performing complex parametric simulations with jEPlus, in: SET2010—Ninth International Conference on Sustainable Energy Technologies, 24–27 August 2010, Shanghai, China, 2010.
[24] Y. Zhang, 'Parallel' EnergyPlus and the development of a parametric analysis tool, in: IBPSA BS2009, 27–30 July 2009, Glasgow, UK, 2009.
[25] DAYSIM, Advanced Daylight Simulation Software, 2013, ⟨http://daysim.ning.com/⟩ (accessed 02.07.13).
[26] Danish Energy Agency, Building Regulations 2010 Ver. 01.01.2013, 2013, ⟨http://www.bygningsreglementet.dk/br10_03/0/42⟩ (accessed 02.07.13) (in Danish).
[27] S.O. Aggerholm, K.E. Grau, SBi-anvisning 213: Bygningers energibehov–Beregningsvejledning, second ed., Danish Building Research Institute, Aalborg University, Aalborg, 2011 (in Danish).
[28] U.S Department of Energy, EnergyPlus Engineering Reference, 2013, ⟨http://apps1.eere.energy.gov/buildings/energyplus/⟩.
[29] R. Peuhkuri, Principles and Specific Challenges of Very Low-Energy Houses in Colder Climates and Corresponding Residential Concept Houses, in: Proceedings of the fourth Nordic Passive House Conference, 17–19 October 2011, Helsinki, 2011.
[30] G.C.J. Skarning, S. Svendsen, C.A. Hviid, Investigation and description of European buildings that may be representative for nearly zero energy single family houses in 2020, in: Proceedings of the CISBAT Conference, 4–6 September 2013, Lausanne, 2013.
[31] L. Vanhoutteghem, S. Svendsen, Modern insulation requirements change the rules of architectural design in low-energy homes, Renewable Energy 72 (2014) 301–310.
[32] J.M. Jensen, H. Lund, Design Reference Year, in: DRY—et nyt dansk reference år. Technical Report lfv-281, Technical University of Denmark, 1995 (in Danish).
[33] C.E. Ochoa, M.B.C. Aries, E.J. van Loenen, J.L.M. Hensen, Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, Appl. Energy 95 (2012) 238–245.
[34] H. Alwaer, D.J. Clements-Croome, Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings, Build. Environ. 45 (2010) 799–807.
[35] K. Alanne, A. Salo, A. Saari, S.-I. Gustafsson, Multi-criteria evaluation of residential energy supply systems, Energy Build. 39 (2007) 1218–1226.
[36] J. Toftum, R.V. Andersen, K.L. Jensen, Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions, Build. Environ. 44 (2009) 2009–2016.
[37] J. Mardaljevic, Examples of climate-based daylight modelling, in: Proceedings of the CIBSE National Conference, 21–22 March 2006, London, 2006.
[38] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Light. Res. Technol. 41 (3) (2009) 261–283.
[39] C.F. Reinhart, J. Mardaljevic, Z. Rogers, Dynamic daylight performance metrics for sustainable building design, Leukos 3 (2006) 1–25.
[40] British Standard, BS8206-2:2008. Lighting for Buildings—Part 2: Code of Practice for Daylighting, 2009.
[41] J. Mardaljevic, J. Christoffersen, A roadmap for upgrading national/EU standards for daylight in buildings, in: Proceedings of the CIE Centenary Conference, 15–16 April 2013, Paris, 2013.

Paper 3

"Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe"

G.C.J. Skarning, C.A. Hviid and S. Svendsen

Published in: *Energy & Buildings 116 (2016) 602-613*

Energy and Buildings 116 (2016) 602–613

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe

Gunnlaug Cecilie Jensen Skarning*, Christian Anker Hviid, Svend Svendsen

Technical University of Denmark, Department of Civil Engineering, Brovej, Building 118, Kgs. Lyngby DK-2800, Denmark

ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
15 December 2015
Accepted 27 January 2016
Available online 2 February 2016

Keywords:
Roof windows
Glazing properties
Window size
Orientation
Space heating demand
Climate-based daylighting
Adaptive thermal comfort

ABSTRACT

Windows are central for the development of liveable nearly zero-energy homes and require careful consideration. Various studies have indicated that the effect of windows on energy consumption may change significantly with improved building insulation levels. Current guidelines on windows may therefore not apply in very well-insulated buildings, and more up-to-date information is needed about window solutions that are appropriate for the new conditions. This study maps the effect of multiple combinations of window size and basic glazing—and frame properties on energy, daylighting and thermal comfort in nearly zero-energy houses located in the European cities Rome and Copenhagen. The aim was to identify options that can support the easy and robust design of future homes with typical use of roof and façade windows. Hourly daylight levels were calculated in DAYSIM, while space heating demand and operative temperatures were calculated in EnergyPlus. The results support previous findings on the limited ability of nearly zero-energy buildings to utilise solar gains. It was found that *U*-values are becoming increasingly important for the energy performance of windows. The paper sketches the increased flexibility and related possibilities that may appear with improved roof window frame constructions and glazing *U*-values far lower than currently standard levels.

1. Introduction

Ambitious strategies for energy conservation in the building mass are now a part of European Union legislation. In 2010, a recast of the Energy Performance of Buildings Directive was adopted stating that all new buildings will be required to consume 'nearly zero-energy' by the end of 2020 [1]. It is the responsibility of the member states to specify cost-efficient nearly zero-energy regulations for their buildings in accordance with future energy prices, discount rates and local energy production systems. At the same time, it is important to make sure that decisions made throughout this process will support healthy and comfortable homes. Windows have a considerable and often complex impact on both energy consumption and the indoor environment, so their role in this development is central. A number of studies [2–4] have indicated that the energy performance of windows in residential buildings may change significantly with improved building insulation level, so that what seem common-sense design rules for windows today may not apply for nearly zero-energy buildings or may be superseded by better options. A recent state-of-the-art review by Jelle et al. [5] of existing glazing products and technologies on the market today identified some promising fenestration techniques and options. However, to be able to identify which of these options that will be useful in nearly zero-energy residential buildings, more knowledge is needed about the combined effect of basic glazing properties and window design parameters on energy, daylighting and thermal comfort. Current guidelines suggesting large and clear south-oriented windows may have to be discarded and replaced with up-to-date information about the energy performance of windows in future European homes.

Research on the energy performance of windows in residential buildings used to focus on reduced window sizes and improved *U*-values, and then started to regard the window as a way of utilising solar energy. With the concept of Zero-Energy Windows [6] and the introduction of new methods for labelling windows in accordance with their net-energy gain [7–9], attention was next drawn to energy-neutral windows with slim frames and high solar energy transmittance (*g*-value). Studies on the effect of window size and distribution for different glazing types came to the conclusion that large south-oriented windows could reduce space-heating demand, both in colder climates with low solar irradiation [10] and in central to southern European climates [11]. Similarly, a guideline from the UK on sloping roof windows in a typical loft room [12] found slightly larger window sizes for optimum energy use than for

* Corresponding author.
E-mail address: gujs@byg.dtu.dk (G.C.J. Skarning).

http://dx.doi.org/10.1016/j.enbuild.2016.01.038

daylighting. Furthermore, Jaber & Ajib [13] showed that optimum window size depends on the thermal properties of the glazing, but for existing triple energy-glazing in the climate of Berlin, they found that increasing the window size facing south always reduced space heating demand. Such rules for energy-neutral windows and their use, however, seem to change in homes with higher insulation levels. Inanici & Demirbilek [2] investigated the optimum window area facing south in relation to various insulation thicknesses for several climates in Turkey. In general, they found that large windows reduce space heating demand for lightly insulated buildings in cold regions, but that the positive effect of large windows diminishes after a certain level of insulation. Another study by Persson et al. [3] investigated the effect of window size in very well-insulated passive houses in Sweden. They found that the size of south-oriented windows is not as important for heat gains as is traditionally assumed. Moderate heat contributions from south-oriented windows can significantly reduce space heating demand, but the heating demand in buildings with this insulation level is so low that very small amounts of the available solar energy can be utilised. They suggest that the focus when designing very well-insulated homes should be on avoiding overheating. These findings were later supported by a study by Vanhoutteghem & Svendsen [4] of very well-insulated single-family houses in Denmark, which found that windows can be oriented freely in different directions without significantly affecting space heating demand. Both of the latter studies also indicated that the effect of high g-values on space heating demand tends to diminish beyond a certain limit. Similarly, Ihm et al. [14] studied the effect of U- and g-values on the combined space heating and cooling demand in a residential building in a northern and southern climate in Korea, and found that g-values above a certain limit either heavily increased energy consumption or had no effect. As part of the increasing attention to overheating resulting from large south-oriented windows, a number of studies have emphasized the importance of using dynamic control strategies for venting and solar shading to create homes with visual and thermal comfort, while still permitting the efficient use of daylight and solar energy [15,16]. Other studies [4,17] have suggested that the importance of dynamic solar shading in low-energy buildings is debatable, due to the reduced need for solar gains. They suggest that glazing with low g-values and solar control coating could be used as a cheaper and more robust means of preventing overheating in such buildings. Furthermore, a recent parametric study by Tsikaloudaki et al. [18] on the energy performance of windows in Mediterranean regions focused on the effect of thermal and optical properties of glazing on the energy demand for cooling.

While for office buildings, there are several examples of studies paying attention to whether the window options investigated are comparable in terms of daylighting and criteria for visual or thermal comfort [19–22], such studies are few for residential buildings. Seen in the light of the tendency that large and clear south-oriented windows in very well-insulated dwellings are becoming less important for reducing space heating demand and more critical for thermal comfort, we believe that such investigation is essential also in residential buildings for achieving a balanced overview of future options. The present study therefore focuses on the possibilities of improving the energy performance of window options that provide well-lit and comfortable spaces toward all orientations, to an extent where nearly zero-energy targets can be met in a robust way. In a parametric study of façade window design in single-family houses in Denmark [23], Vanhoutteghem and the present authors have previously reported a method for carrying out such investigation that makes it possible to illustrate and compare the combined effect of multiple combinations of window parameters on energy, daylighting and thermal comfort. The study considered several different room geometries and found that it is difficult to achieve adequate daylighting without overheating in south-oriented rooms deeper than 4–5 m. In the present study, we aim to provide a broader overview of the energy performance of windows in nearly zero-energy houses in Europe. This is why the study includes two geographical locations, Rome and Copenhagen. Our intention is to map and identify the window characteristics that are likely to contribute most to the energy performance of nearly zero-energy houses using roof and façade window options that permit high-quality daylight conditions without overheating when considering a building with reasonable room-layout for daylighting. While our previous study only included façade windows, the present study considers a section of a 1½-storey single-family house that may represent typical use of both roof and façade windows in future residential buildings (Fig. 1). Dynamic solar shading devices were not included in the study. Instead, overheating was reduced by means of glazing products with appropriate g-values and various abilities to separate the transmission of visible light from that of solar energy. The main focus in the paper is the transparent part of the windows, i.e. the glazing, as this faces the most complex challenges in optimising daylighting, thermal comfort and energy consumption at the same time. However, since roof windows are a central part of this study, the investigation also includes variations on the thermal performance of roof window frame constructions (including junctions between roof and window). These account for heat losses similar in level to the heat losses through the whole of the rest of the building envelope of the rooms they are installed in, and may in that way affect the energy consumption of the spaces considerably, which again may influence the possibilities of finding robust solutions for the glazed part.

2. Methodology

The building section considered (Fig. 1) consists of two different zone types (A-B) that were modelled as separate units with single-sided daylighting access and venting possibilities. Model A is a side-lit space on the ground floor with façade windows, whereas Model B is a loft room on the 1st floor with 45-degree-sloped roof

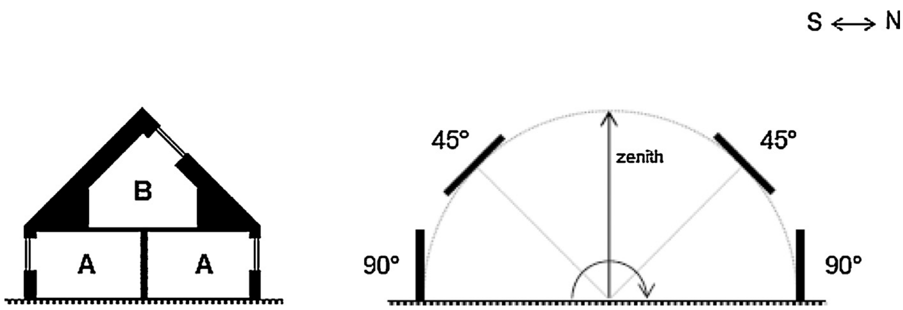


Fig. 1. Vertical section of a 1½-storey single-family house indicating the spaces A-B with typical use of roof and façade windows and the related combinations of window slope and orientation.

Table 1
Variables used for parametric analysis.

Parameter	Rome	Copenhagen
Frame construction–façade windows (90°)	A1	A1
Frame constructions–roof windows (45°)	B1 B2 B3	B1 B2 B3
Orientation	S N	S N
Glazing-to-floor ratio[a] (%)	5 10 15 20 25 30 35	5 10 15 20 25 30 35
Glazing U-value (W/m^2 K)	0.7 0.9 1.1 1.3	0.3 0.5 0.7 0.9
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 (-)	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

[a] Fraction of internal floor area and for daylighting modelled with 2.5% increments.

windows in one of the two roof surfaces. Studies on the significance of thermal zoning for the prediction of energy performance and the thermal environment [4,24,25] have demonstrated that modelling single-family houses as a single zone leads to both underestimation of space heating demand and overheating. As a minimum, these studies suggest that rooms with and without direct solar exposure should be modelled separately. In practice, the various spaces in a real house can take advantage of each other through various amounts of heat and air exchange, but a reasonable starting point for robust development is to identify window solutions that also perform well in houses where such interaction is limited. The floor dimensions for both models were 4 × 4 m and the internal volume of each model was 40 m^3. These dimensions can be considered a reasonable layout for daylighting. Since the building section considered is located in the middle of the house, where heat losses are smaller than the average for the whole house, the models represent relatively difficult cases for the utilization of solar energy gains and the avoidance of overheating.

2.1. Location and climate

Simulations were performed for two different European climates, based on weather data for Rome and Copenhagen. Outdoor temperatures and solar elevation angles are higher in Rome than in Copenhagen, and the cumulative annual access to daylight and solar irradiation increases almost linearly from the Scandinavian climate in Copenhagen (latitude 55.63) to the South-European climate in Rome (latitude 41.80) [26].

2.2. Performance parameters for energy, daylighting and thermal comfort

The study considered homes in which mechanical cooling had not been installed. Energy use was evaluated on the basis of space heating demand alone and was expressed in kWh/m^2 per year. In Denmark, the annual primary energy usage for covering space heating, domestic hot water and electricity for pumps and ventilation in nearly zero-energy residential buildings is defined as no more than 20 kWh/m^2, which refers to the energy usage after the primary energy factors of 0.6 for district heating and 1.8 for electricity have been applied. This means that an acceptable space heating demand (or end energy usage for heating) of the building section considered is approximately 10 kWh/m^2 per year, when the larger heat losses of rooms in building corners have been taken into account. The goal for the maximum space heating demand was assumed to be the same in Rome [17]. It was further assumed that the occupants were free to use windows for venting, adjust their clothing, and in other ways adapt to indoor conditions. The adaptive thermal comfort (ATC) model in EN 15251 [27] was therefore used to quantify overheating. 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. In accordance with standard practice procedures in Denmark for documenting thermal comfort in dwellings [28], overheating was deemed to have occurred when operative temperatures in the rooms exceeded the upper comfort limit provided by class II of this model for more than 100 h per year. For office spaces, Cappelletti et al. [20] showed that solar irradiance through windows may increase the hours of discomfort in positions near window surfaces. Such effects have not been accounted for in this study.

The establishment of reasonable daylight criteria is an issue that is under continuous debate, supported by ongoing research on the effects of daylighting on human health [29,30]. For this research, we assumed that the daylighting was acceptable if 75% of a horizontal plane 0.85 m above floor level received at least 300 lux in 50% of the daylight hours. This assumption is in coherence with the diffuse daylight access suggested by Mardaljevic and Christoffersen [29] and with the recently established recommendations by IES for Spatial Daylight Autonomies in offices [31]. The use of daylight hours instead of office hours for evaluating the occurrence in time, however, implies slightly larger windows than would be found using this metric exactly as defined for offices.

2.3. Parameter variations

On the basis of the two room models (A-B), all combinations of the variables given in Table 1 were investigated for both climates. The façade windows were modelled using frame construction A1 (Table 2), whereas the roof windows were modelled for three different frame constructions (B1–B3). These were: an extremely well-insulated construction not yet in existence (B1), a very well-insulated state-of-the-art-construction (B2) and the

Table 2
Thermal properties of the frame constructions investigated for façade and roof windows.

Window type and slope[a]	Room model	Frame construction	Frame properties				
			Width (m)	U-value (W/m^2 K)	Psi g (W/m K)	Psi w (W/m K)	Specific heat loss[b] (W/K)
Façade 90°	A	A1	0.09	0.8	0.035	0.01	0.583
		B1	0.09	0.5	0.025	0.01	0.399
Roof 45°	B	B2	0.11	0.7	0.025	0.05	0.768
		B3	0.09	1.5	0.050	0.10	1.460

[a] Angle given relative to horizon.
[b] Specific heat loss of frame (including the effect of junction between frame and glazing and junction between window and wall/roof), calculated on the basis of a reference window with outer dimensions 1.23 by 1.48 m.

Table 3
Building specifications for the thermal simulation model.

	Rome	Copenhagen
Constructions		
U-value wall[a] (W/m^2 K)	0.28	0.13
U-value roof[a] (W/m^2 K)	0.15	0.08
U-value floor[a] (W/m^2 K)	0.10	0.10
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 venting rate (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

[a] Includes linear heat losses.

frame construction typically used for roof windows today (B3) (Table 2). Hourly illuminance levels were calculated by means of the RADIANCE-based daylighting analysis tool DAYSIM [32] for a sensor point mask-width of 0.2 m. For the calculation of space heating demand and operative temperatures, the building simulation tool EnergyPlus [26] was used in combination with the tool jEPlus [33,34] for parametric analysis. EnergyPlus has been widely validated and is an acknowledged simulation tool that uses the heat balance model to predict thermal loads in buildings. All the rooms were modelled with two windows, consistently distributed and centred on the width, and the windows were always positioned as close to the top edge of the façade or roof surface as possible for optimal diffuse daylight access. In daylight calculations, the depth of all window sills was assumed for simplicity to be 0.45 m in both climates, although wall and roof thicknesses in the thermal simulations (Table 3) were approximately 0.35 and 0.30 m in Rome and 0.45 and 0.55 m in Copenhagen. No external obstructions were taken into account, and the reflectance of surfaces was assumed to be 70% for walls and ceilings and 30% for floors. The properties of glazing and frames were modelled in EnergyPlus, using the Simple Glazing System material [35]. This approach allows the thermal and optical properties of windows to be described generically by performance indices such as *U*-value and *g*-value where a realistic layer-by-layer description of the glazing is not available. Linear interpolation was used to extract final boundaries for daylighting and thermal comfort from DAYSIM and EnergyPlus output-files.

2.4. Specifications for building envelope and system properties

Building envelope and system properties (Table 3) were selected on the basis of an earlier study of European nearly zero-energy reference buildings by the present authors [17]. The models assumed ambitious heat recovery efficiency and high-quality construction details. With the thermal properties of construction selected, the annual space heating demand of the building section considered without windows was approximately 4 kWh/m^2 in both climates. Windows were assumed to open automatically whenever indoor operative temperatures exceeded the venting set point (Table 3). Heating set-point and design values for internal gains were chosen in accordance with standard practice in Denmark [28]. The heating power to achieve the heating set point was assumed to be infinite by using the Ideal Loads Air System in EnergyPlus, and the operative temperatures used for evaluation of thermal comfort were achieved using the default Zone Averaged calculation type for the mean radiant temperature of the space [36]. Weather data from the Danish Reference Year [37] were used for Copenhagen, and weather data from the U.S. Department of Energy's homepage [26] were used for Rome.

2.5. Coupling of the results—the glazing diagram

The useful combinations of glazing-to-floor-ratio and glazing g-value, i.e. those that permit 75% of the space to achieve 300 lux in 50% of the daylight hours without overheating, can be identified for different window types with different orientations and thermal properties by using the glazing diagram presented in Vanhoutteghem et al. [23]. The diagram is explained in Fig. 2 and basically consists of three layers: one for space heating demand, one for thermal comfort and one for daylighting. When these three layers are put together, the space heating demand of the rooms in kWh/m^2 per year for the combinations of glazing *g*-value and glazing-to-floor ratio under investigation can be evaluated in relation to a *solution space* formed by the limits for daylighting and thermal comfort.

In the diagram, each light transmittance value is coupled to a range of *g*-values based on two selected rules for the relationship between transmittance of light and solar energy. This relationship, also referred to as *selectivity for daylight* [38], provides information about the ability of a glazing product to separate between the transmittance of visible light and solar energy. Approximately, half the solar irradiation that can pass through glazing is visible light, and it is not physically possible to develop glazing products with a g-value that is less than half the light transmittance [38]. The lower boundary for the *g*-value (6) is therefore a finite limit that several solar control glazing products on the market today approach quite closely (Fig. 2). The upper limit for daylight efficiency (7) is not a physical limitation and merely indicates optimal products when solar irradiation is desirable. The reader can use this boundary (7), where the *g*-value equals light transmittance, to connect the vertical lines showing minimum glazing sizes for daylighting with their respective light transmittance values. Throughout this paper, however, the first line from the left will always correspond to 70% LT.

3. Results and discussion

Figs. 3–5 illustrate the results achieved in Copenhagen for façade windows (Model A) and for roof windows (Model B) oriented south and north, respectively, for the full range of glazing *U*-values and frame constructions investigated. Fig. 6 illustrates, as an example for Rome, the results for the two window types oriented south and north with a *U*-value of 0.9 W/m^2 K and frame constructions A1 and B3. The aim of the first section in the following is to introduce the reader to the solution spaces found for the different window types, orientations and climates, and how these should be understood. Based on these useful solutions identified for daylighting and thermal comfort, the next section discusses the potentials for reducing space heating demand by improving glazing *U*- and *g*-value in different parts of the building. Finally, the last section points at two different approaches to the development of window products that meet nearly zero-energy targets and exemplifies thermal properties of glazing and frame that would be required with each of these.

3.1. The useful options for daylighting and thermal comfort

Daylighting and thermal environment were modelled under realistic outdoor sun and sky conditions. Therefore, Figs. 3–6 show that every combination of climate, window type and orientation has a solution space with its own boundaries for daylighting and thermal comfort. The design options in the rooms most heavily exposed to direct sun (e.g. a room with south-oriented roof windows in either climate) are limited to small *g*-values and small glazing-to-floor ratios due to overheating. If the windows are

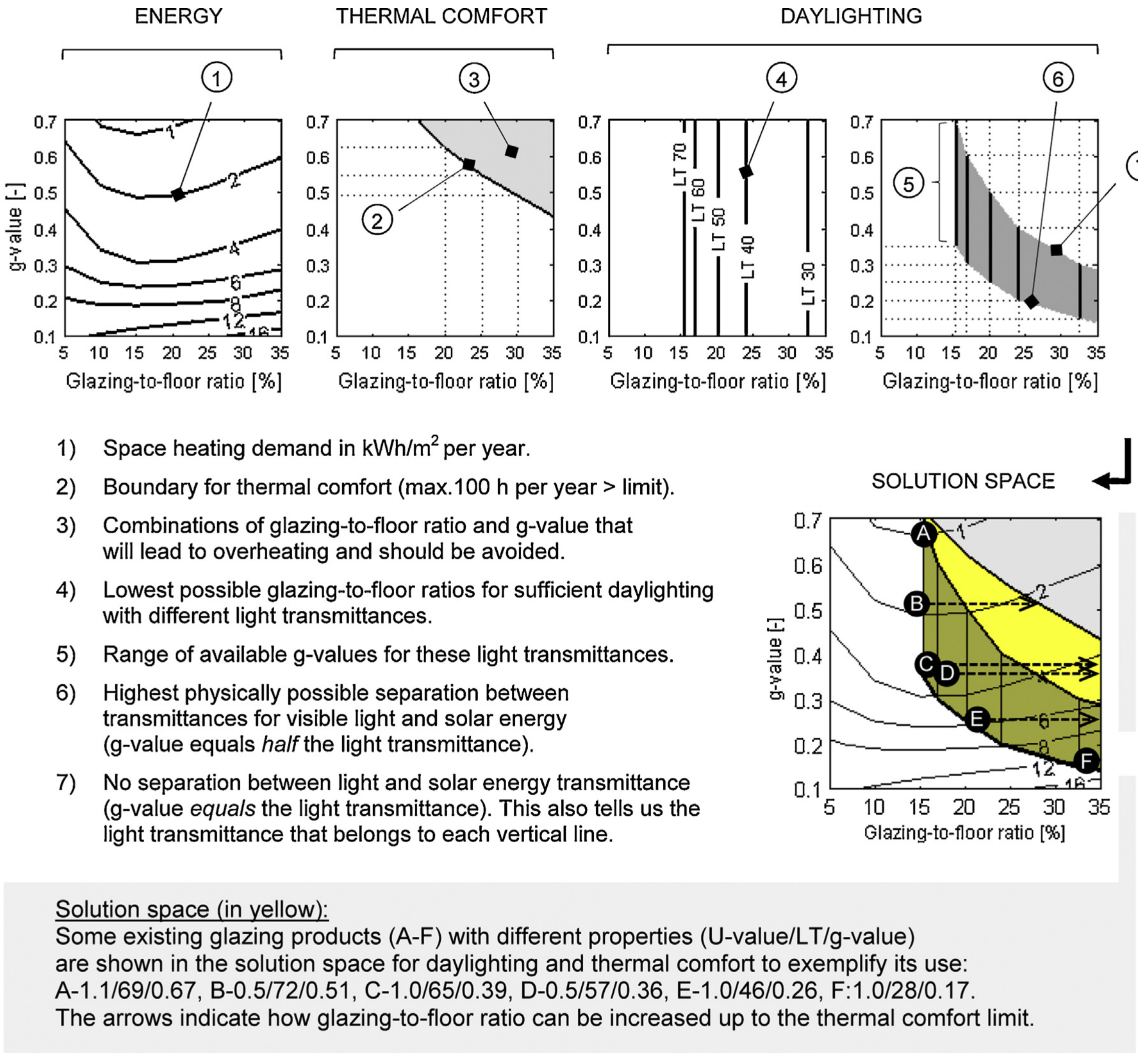


Fig. 2. Reader's guide to the glazing diagram.

carefully sized for the exact fulfilment of the daylight target, however, it is possible to find options that will fulfil the daylight target without overheating by choosing a glazing with an appropriately low g-value and some selectivity for daylight. For the south-oriented roof windows, one such option might be a glazing corresponding for example to Product E in Fig. 2 with a g-value of 0.26. With a light transmittance of 46%, this glazing must be dimensioned for glazing-to-floor-ratios of approximately 14–16% in Copenhagen and 8–10% in Rome to meet the daylight target without overheating (Line A, Figs. 4 and 6). It should be borne in mind though, that a very narrow solution space still means a large risk of either overheating or less daylighting, so in this case a slightly more flexible option in terms of indoor climate would be to use a north-oriented roof window. With the solar heights in Rome, however, even a north-oriented roof window is exposed to direct sun and has a solution space similar to that of south-oriented façade windows (Fig. 6).

The largest solution spaces were found in rooms with windows that are not exposed to direct sun. Here, no selectivity for daylight is needed (i.e. the g-value can equal LT), and it is possible to use larger glazing-to-floor ratios than the minimum for daylighting. For example, for the sloped north-oriented roof window in Denmark, a typical option could be a triple energy-glazing, such as Product B in Fig. 2. With this g-value of 0.51, glazing-to-floor ratios can exceed 35% without overheating (Line A, Fig. 5). This would give significantly more daylighting than targeted, because a glazing-to-floor-ratio of 12–13% would have been sufficient to meet the daylight target with the light transmittance of 72% for this product.

3.2. *The importance of glazing* U- *and* g-*value for reducing space heating demand*

By studying the contour lines in Figs. 3–6, it may be seen that the potential savings in space heating demand by changing different parameters for a certain window type and orientation vary with thermal properties of glazing and frame, glazing size and g-value, and tend to diminish as the space heating demand reaches the low levels typically found in solar-exposed rooms for smaller windows with g-values in the range 0.3–0.5. If, for example, large glazing solutions with energy consumption close to the targeted space heating demand are considered (here 10 kWh/m^2), increasing glazing g-value by 0.1 reduces energy consumption by up to 4–5 kWh/m^2 per year in the south-oriented rooms with roof and façade windows in Copenhagen (Lines A-C in Fig. 3, and Lines B-C in Fig. 4). If taking a more typical window option with LT 70% and g-value 0.4 dimensioned for minimum daylighting, however, the energy savings per change in g-value of 0.1 would range from less than 0.2 kWh/m^2 per year for the most insulated façade window (Line D, Fig. 3) to at most 2 kWh/m^2 per year for the least insulated roof window (Line D, Fig. 4). To compare the

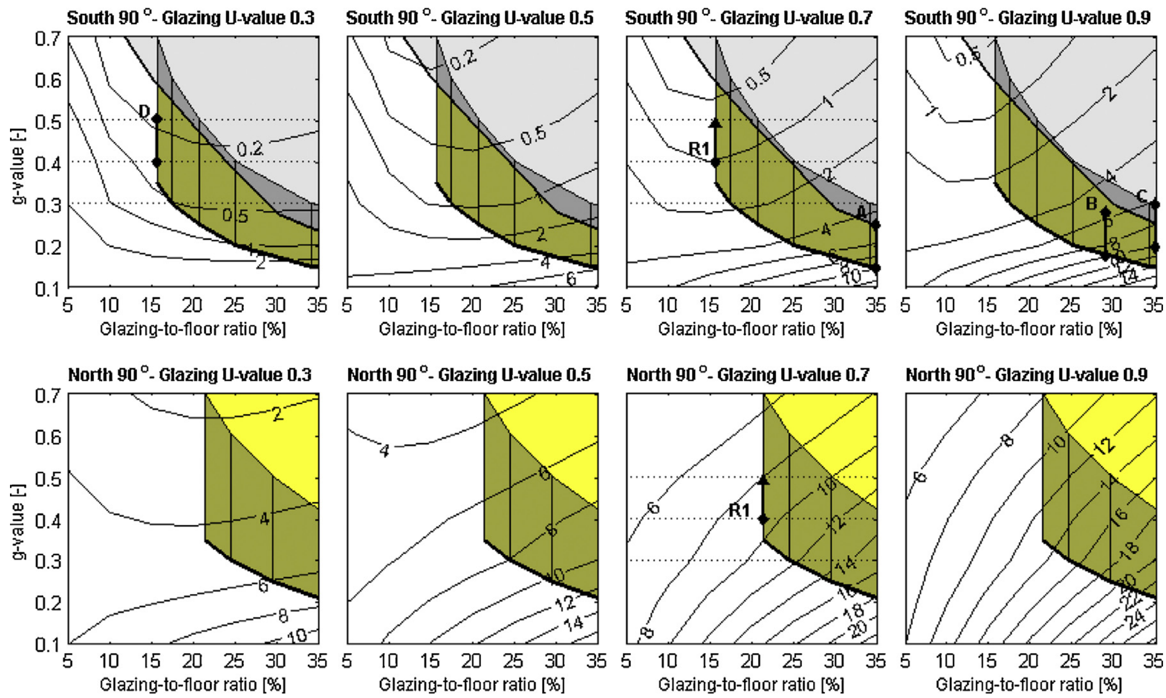


Fig. 3. Solution spaces for the façade window in Copenhagen-oriented south (top) and north (bottom) with glazing U-values of 0.3–0.9 W/m^2 K and frame construction A1.

energy-saving potentials in glazing U- and g-value for such typical roof and façade windows in building parts with different orientation, Table 4 gives an overview of the savings in space heating demand by either increasing the g-value or decreasing the glazing U-value by 0.1 with basis in three reference points (R1–R3). In Copenhagen, R1 (Fig. 3) represents a façade window option with triple energy-glazing, while R2,R3 (Figs. 4 and 5) represent roof window options with state-of-the-art thermal properties and the best thermal properties commonly available on the market today, respectively. In Rome, the same references are used, but with higher glazing U-values. All references assume windows with LT 70% and g-value 0.4 dimensioned for minimum daylighting, and it should be kept in mind that increasing the g-value from 0.4 to 0.5 leads to overheating slightly above the limit in south-oriented rooms with roof windows. Table 4 also indicates the importance of increasing the g-value relative to decreasing the glazing U-value, and the weight of the absolute savings in space heating demand relative to the targeted space heating demand for the building section in total of 10 kWh/m^2 per year.

Looking at the relative importance of parameters in south-oriented rooms in Copenhagen, Table 4 shows that increasing the g-value reduced space heating demand by two to three times more than decreasing the U-value. This means that g-value is still the most important parameter of the two in solar-exposed rooms. These numbers are however low compared with the five to six times more energy that can theoretically be gained by increasing the g-value of a sloped south-oriented window surface, than can be saved by improving the U-value of the surface [8]. This indicates that south-oriented rooms with nearly zero-energy consumption can only utilise approximately half of the solar gains previously assumed fully usable in heating-dominated residential buildings and used as a basis for energy labelling of windows in Denmark [8]. In north-oriented rooms, g-value was 1–1.7 times more important than the U-value.

Comparing the absolute savings in space heating achieved per change in glazing U- or g-value for roof- and façade windows with different orientations (Table 4), it may furthermore be seen that the savings by increasing the g-value in south-oriented rooms in Copenhagen account for 4–18% relative to the targeted space heating demand, while the same savings in north-oriented rooms account for 13–20%. This means that, even though the g-value is still at least twice as important as the U-value in solar-exposed rooms, the absolute energy savings by improving both parameters are just as important (or more so) for reducing space heating

Table 4
Reductions in space heating demand in kWh/m^2 per year by increasing glazing g-value by 0.1 (dg) or decreasing glazing U-value by 0.1 (dU_g) for some typical references R1–R3 with g-value 0.4 and minimum glazing size for daylighting with LT 70%. The table also indicates the importance of increasing the g-value relative to decreasing the U-value (dg/dU_g) and the weight of the absolute savings per change in each parameter relative to the targeted space heating demand for the building section in total of 10 kWh/m^2 per year (E_t).

Window type and reference[a]			Rome					Copenhagen				
			dg	dU_g	dg/dU_g	dg/E_t	dU_g/E_t	dg	dU_g	dg/dU_g	dg/E_t	dU_g/E_t
Façade 90°	South	R1	0.3	0.1	4.8	3%	1%	0.4	0.2	2.0	4%	2%
	North	R1	1.2	0.5	2.4	12%	5%	1.4	1.3	1.0	14%	13%
Roof 45°	South	R2	0.6	0.1	5.9	6%	1%	0.9	0.5	2.0	9%	5%
		R3	0.9	0.1	7.4	9%	1%	1.8	0.6	2.9	18%	6%
	North	R2	1.0	0.4	2.6	10%	4%	1.3	1.1	1.1	13%	11%
		R3	1.3	0.4	3.4	13%	4%	2.0	1.2	1.7	20%	12%

[a] Frame type and glazing U-value (U_g) in W/m^2 K for the references. In Rome: R1 (A1, U_g 1.1), R2 (B2, U_g 0.9), R3 (B3, U_g 1.1). In Copenhagen: R1 (A1, U_g 0.7), R2 (B2, U_g 0.5), R3 (B3, U_g 0.7), as indicated in Figs. 3–5.

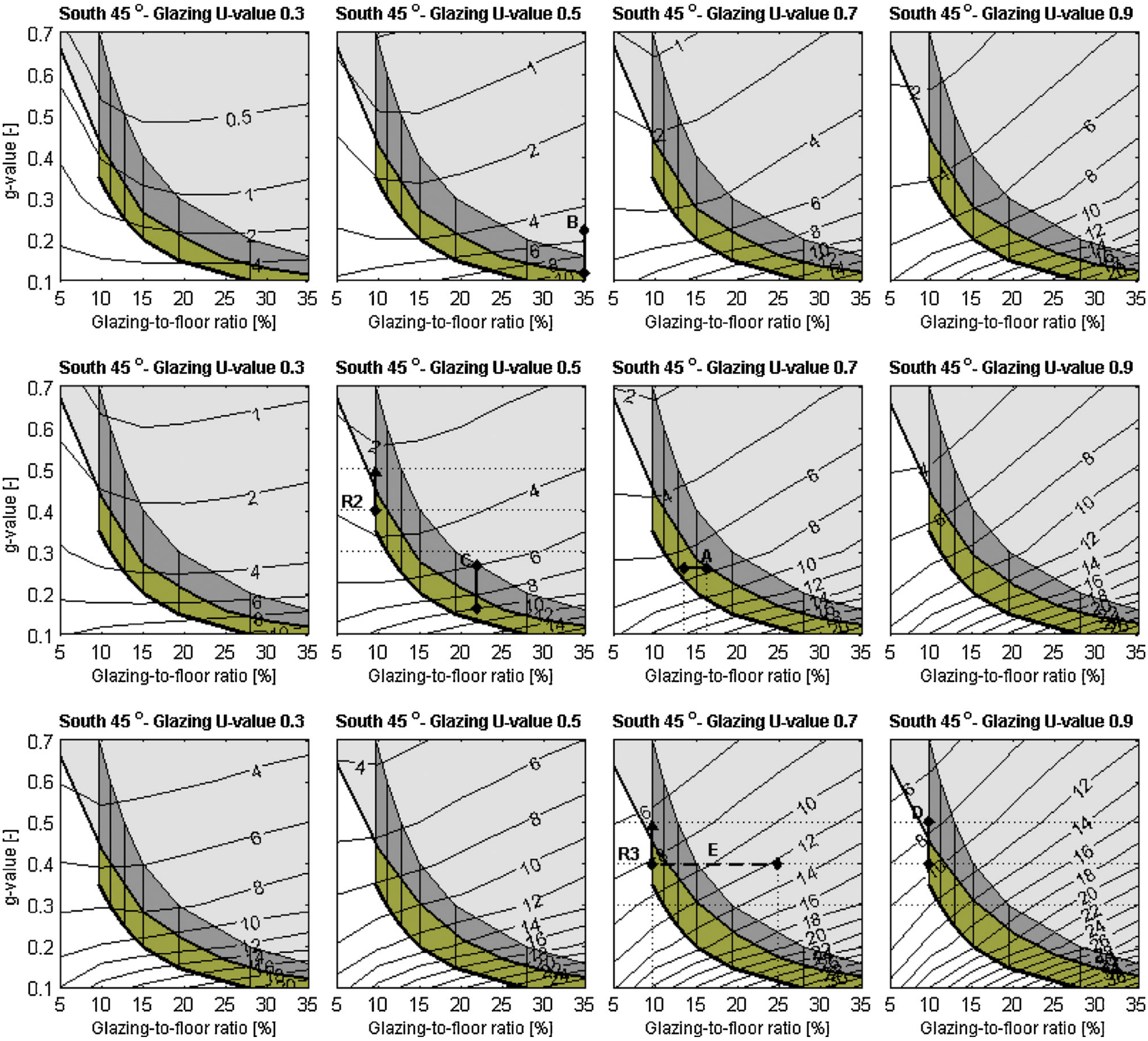


Fig. 4. Solution spaces for the 45-degree-sloped roof window in Copenhagen-oriented south with glazing *U*-values of 0.3–0.9 W/m[2] K and frame constructions B1 (top), B2 (middle) and B3 (bottom).

demand in north-oriented rooms as in south-oriented rooms, due to the differences in space heating demand between the two orientations. For façade windows, glazing *U*- and *g*-value in north-oriented rooms held approximately three times the saving potential as that of increasing solar gains in south-oriented rooms, while for the loft rooms with roof windows (and an overall larger space heating demand than the ground floor), the saving potential was nearly equal for both orientations.

Another observation related to the importance of *U*- and *g*-value is that glazing sizes exceeding a certain optimum increase space heating demand in both north- and south-oriented rooms (Figs. 3–5). For example, if a *g*-value of 0.4 for the south-oriented roof window in Copenhagen could be combined with a larger glazing-to-floor-ratio without any risk of overheating, this would not lead to energy savings due to increased access to solar gains, but instead would increase the energy demand for space heating (Line E, Fig. 4). The useful amount of solar irradiation cannot compensate for the increased heat losses with larger windows, even though the glazing *U*-values considered in this study are low relative to standard practice. This contradicts existing guidelines recommending large and clear south-oriented glazing for energy reduction and indicates that *U*-value is becoming increasingly important for the energy performance of windows. As glazing *U*-value decreases (Figs. 3 and 4), the optimum glazing size for space heating may be seen to cover a larger range of glazing-to-floor ratios and move towards larger glazing sizes. In this way, improved *U*-values can help reduce the negative effect of large window areas. With sufficiently low *U*-values, the optimum glazing size for space heating will match the solution space for daylighting and thermal comfort so well that window size can be chosen relatively freely with very small effect on energy consumption.

In Rome, the tendencies were similar. With the lower insulation level and the warmer and sunnier climate, the *g*-value was up to seven times more important than the *U*-value in solar-exposed rooms. If comparing the saving potential in different building parts, however, reductions in space heating demand per change in both parameters were larger in north-oriented rooms than in south-oriented rooms, but for all room types, the *g*-value was considerably more important than the *U*-value. Furthermore, window size had only limited effect on space heating demand and could be chosen

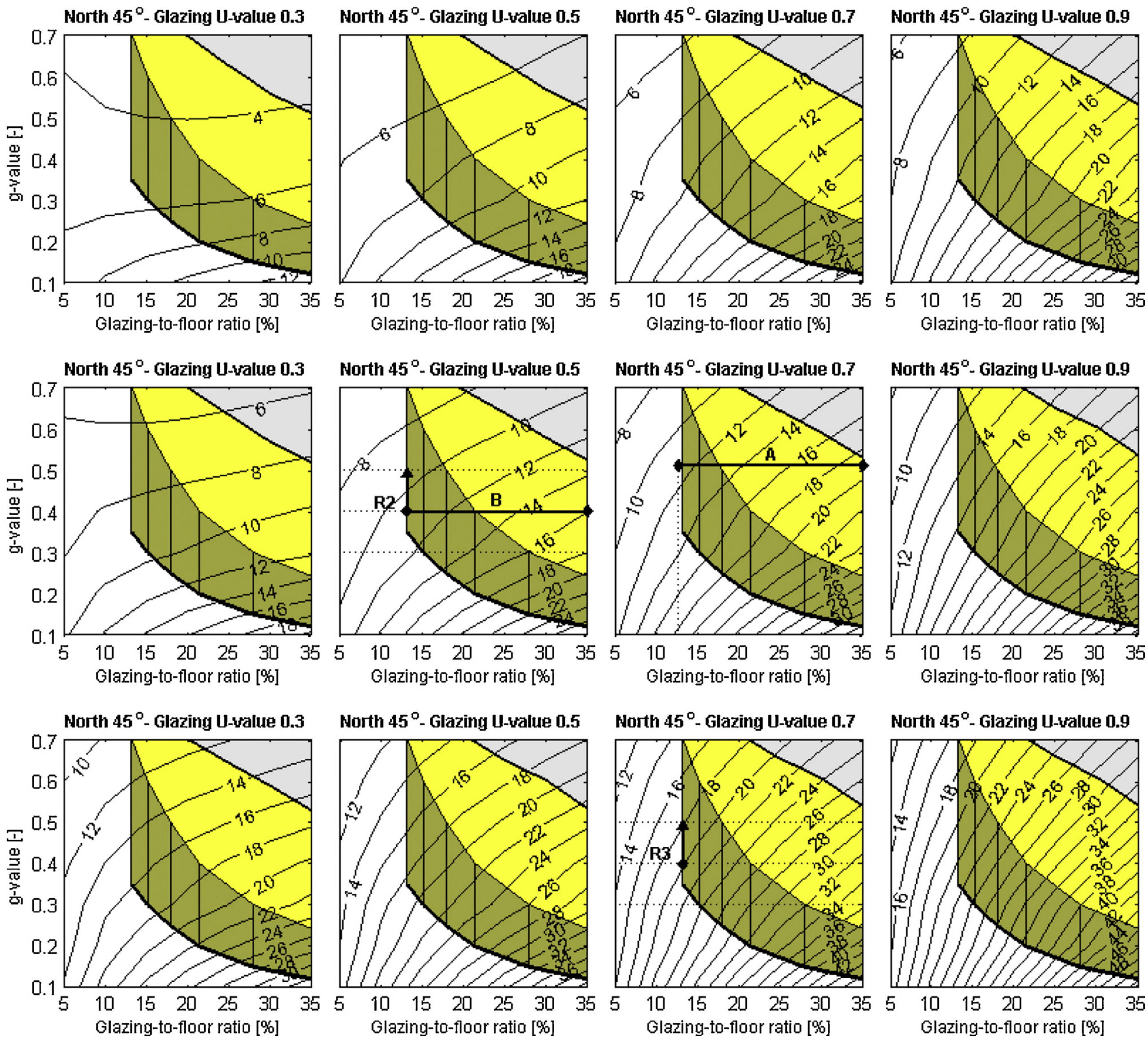


Fig. 5. Solution spaces for the 45-degree-sloped roof window in Copenhagen-oriented north with glazing *U*-values of 0.3–0.9 W/m^2 K and frame constructions B1 (top), B2 (middle) and B3 (bottom).

relatively freely within the boundaries for daylighting and thermal comfort. Similar to the findings by Gasparella et al. [11], large south-facing windows with the lowest *U*-values could slightly reduce space heating demand, but the tendency was still that large windows towards both orientations slightly increased space heating demand with glazing *U*-values larger than 0.9 W/m^2 K.

3.3. Examples of possible approaches to the development of suitable windows

Table 5 gives an example of thermal properties of glazing and frame that would be sufficient to meet the energy conservation target at building level with varying degrees of flexibility. The example is based on a reasonable weighting of the space heating demand permitted in different parts of the building. For a north–south-oriented section of the one-storey residential building considered in Vanhoutteghem et al. [23], triple-glazing façade windows with *U*-value 0.5–0.7 W/m^2 K were found sufficient to meet an energy conservation target of 10 kWh/m^2 per year with reasonable flexibility. With such façade windows, the average weighted energy consumption of a pair of north–south-oriented rooms at the ground floor in the present study would easily be less than 6 kWh/m^2. This permits the loft rooms to consume approximately 16 kWh/m^2 per year, given that the 1st floor corresponds to 38% of the gross floor area of the house. To address the possibility of using north-oriented roof windows, which are the most robust in terms of thermal comfort, as an individual solution for the loft rooms, Table 5 evaluates roof windows with both orientations based on this target. The numbers in brackets, however, indicate the results if the 1st floor was a mix of north- and south-oriented rooms.

The degrees of flexibility used to identify the thermal properties of glazing and frame in Table 5 are based on two different approaches to the development of windows for nearly zero-energy buildings, suggested in the following.

3.3.1. Well-dimensioned windows with focus on both glazing parameters

One approach would be to use windows with light transmittances in the higher end and make sure that these are carefully

Table 5
Acceptable glazing U-values (in the range of 0.7–1.3 W/m^2 K in Rome and 0.3–0.9 W/m^2 K in Copenhagen) for meeting the targeted space heating demand with varying degrees of flexibility. For roof windows, the U-values in brackets apply if north and south can be averaged.

Window type and frame construction			Reasonable flexibility[a]		Full flexibility[b]	
			Rome	Copenhagen	Rome	Copenhagen
Façade 90°	–	A1	1.3	0.7	0.7	0.3
Roof 45°	South	B1	1.3 (1.3)	0.9 (0.9)	1.3 (1.3)	0.7 (0.5)
		B2	1.3 (1.3)	0.9 (0.9)	1.3 (1.1)	0.5 (0.3)
		B3	1.3 (1.3)	0.9 (0.5)	1.3 (0.7)	< 0.3 (« 0.3)
	North	B1	1.3 (1.3)	0.9 (0.9)	0.9 (1.3)	0.3 (0.5)
		B2	1.3 (1.3)	0.7 (0.9)	0.7 (1.1)	< 0.3 (0.3)
		B3	1.3 (1.3)	0.3 (0.5)	< 0.7 (0.7)	impossible (« 0.3)

[a] Energy target met with LT 40–70% in solar-exposed rooms and LT 60% with g-value 0.4 in rooms without direct sun.
[b] Energy target met with all combinations of g-value and glazing-to-floor ratio within the solution space.

dimensioned for exact fulfilment of the daylighting target. By doing this, window sizes will not be larger than strictly needed for daylighting and g-values can be held relatively high in all room types to favour a low space heating demand. In a solar-exposed room with roof windows, for example, a glazing with LT 70% that is carefully dimensioned for minimum daylighting may have a g-value of 0.4 and still be within the boundaries for thermal comfort (see e.g. R2–R3, Fig. 4). With the flexible solution space in north-oriented rooms, g-value is not limited by thermal comfort and may be considerably higher. In practice, however, the choice is limited to approximately 0.5 for the triple energy-glazing considered, and even less for the multi-pane glazing solutions needed to approach the U-value of 0.3 W/m^2 K, which implies relatively small differences in maximum g-value between the two orientations. With the help of such moderate to high g-values, the energy conservation target can be met with a relatively wide range of thermal properties of glazing and frame. For solar-exposed rooms (which includes the north-oriented roof window in Rome), 'Reasonable flexibility' in Table 5 refers to solutions where the energy conservation target can be met with light transmittances in the range 40–70% without exceeding the boundary for thermal comfort. For the rooms without direct sun 'Reasonable flexibility' is defined as the solutions where the energy conservation target can be met with LT 60% and g-value 0.4.

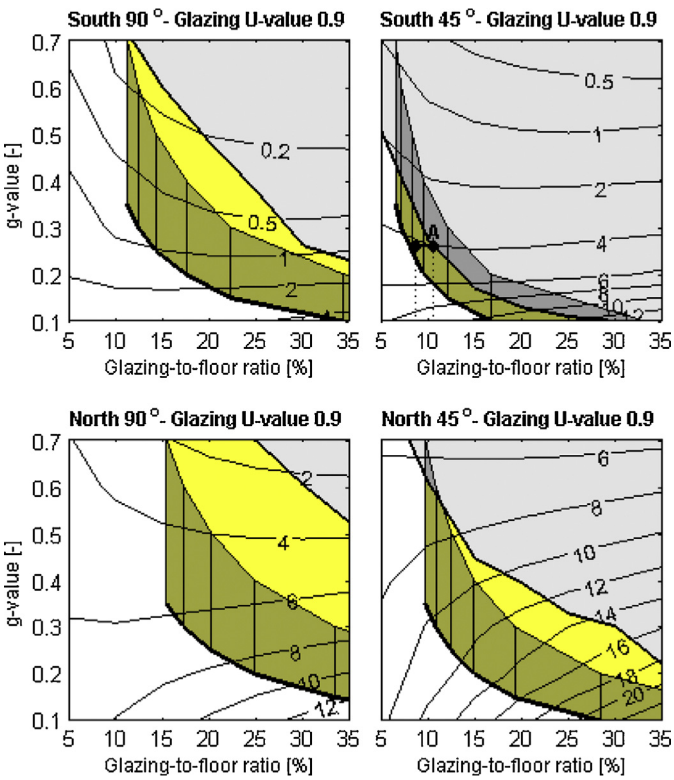


Fig. 6. Example of solution spaces for the two window types in Rome-oriented south (top) and north (bottom) with glazing U-values of 0.9 W/m^2 K. The frame constructions are A1 for façade windows (left) and B3 for roof windows (right).

3.3.2. *Focus on extensively improved thermal properties to increase flexibility*

Seen in the light of the reduced significance of solar gains, another approach would be to focus on improving the thermal properties of glazing and frame to a level where the choice of transmittances will no longer be critical for reaching the energy frame. In solar-exposed rooms, where the options for g-value and glazing size are limited by overheating, the use of larger window areas in combination with transmittances at the lower end of the scale can be critical for meeting the energy conservation target. With thermal properties of glazing and frame that are sufficiently low, however, glazing size and transmittances can be selected freely in terms of space heating demand. In this way, it would be possible to use larger glazing areas with the solar control coating and transmittances needed to achieve thermal comfort, which would open up for improved view out and more even daylight distributions, without the need for supplementary dynamic shading devices. This situation where any combination of glazing size and transmittance tends to meet the energy target is referred to as 'Full flexibility' in Table 5. With the advantages of low U-values discussed in Section 3.2, the improvements in thermal properties of glazing and frame needed to allow 'Full flexibility' will simultaneously increase flexibility regarding window size in both north- and south-oriented rooms. In north-oriented rooms, this flexibility would mean that daylighting could be increased with no limitations regarding overheating and without critically affecting the space heating demand, while in south-oriented rooms this would mean that if window size by different means could be increased without reducing the transmittances, this would only slightly affect space heating demand.

3.3.3. *Thermal properties needed for flexibility in rooms with façade windows*

Studying the façade window options with glazing U-value 0.7 W/m^2 K, which allow the energy target to be met with 'Reasonable flexibility' in Copenhagen (Fig. 3, and Table 5), it may be seen that the minimum glazing-to-floor ratios for daylighting with the higher light transmittances correspond well with optimum glazing sizes for space heating demand. Furthermore, with the options that allow 'Full flexibility' (multi-layer glazing with U-value 0.3–0.5 W/m^2 K), glazing size can be chosen relatively freely in both north- and south-oriented rooms with nearly no effect on space heating demand. In Rome, 'Full flexibility' is achieved with a U-value of 0.7 W/m^2 K, and for this glazing, large windows are slightly better options for space heating demand than the smaller.

3.3.4. Thermal properties needed for flexibility in loft rooms with roof windows

In the loft rooms, space heating demand is naturally higher than for the ground floor. This is both because the room itself has larger heat losses and also because the heat losses are larger through sloped glazing than through vertical glazing. Moreover, heat losses through the roof window frame constructions (including the junction between roof and window) account for a very large part of the space heating demand. Comparing the space heating demand for options that consume less than the targeted 16 kWh/m^2 per year in Copenhagen (Figs. 4 and 5), it may be seen that improving thermal properties of frame constructions from the level of B3 to the level of B2, would reduce space heating demand by 3−5 kWh/m^2 in south-oriented rooms and 6−7 kWh/m^2 in north-oriented rooms. In Rome, these savings are smaller and in the range 0.5−4 kWh/m^2 per year. For the references (R2-R3), the savings by improving frame constructions in Copenhagen and Rome respectively, are two to three times and 1-1.5 times larger than those identified per change in *U*- and *g*-value.

For the glazing-to-floor ratios that give sufficient daylighting, the insulation level of the frame is not seen to affect the consequences of large windows as much as the glazing *U*-value. The large heat losses of the frame, however, lead to an overall higher space heating demand, which may be critical for whether nearly zero-energy consumption can be met at building level. Taking as an example, the north-oriented roof window in Copenhagen with standard frame construction (B3), the energy conservation target of 16 kWh/m^2 can only just be met with a glazing *U*-value of 0.5 W/m^{2}K, and even if multi-layer glazing with *U*-value 0.3 W/m^{2}K would be available on the market, the energy target would barely be met with reasonable flexibility, taking into account the reduced transmittances with more panes. With the very well-insulated frame construction (B2), however, the target can be met with reasonable flexibility with a glazing *U*-value of approximately 0.7 W/m^2 K, and with *U*-value 0.5 W/m^2 K glazing size can be chosen freely when *g*-values are above 0.4 (Line B, Fig. 5). If the frame construction could be further improved to the level of B1, full design flexibility would be close with a U-value of 0.3−0.5 W/m^2 K. If the roof window is oriented south, on the other hand, (which increases the risk of overheating), all combinations of *U*-value and frame construction investigated would be sufficient to meet the energy target. With frame construction B2, however, it would be possible to achieve full flexibility with a *U*-value of 0.5 W/m^2 K. These thermal properties are the same as those found to allow free choice of glazing size in north-oriented rooms.

In Rome, the use of a better frame construction than the standard would not add anything for the south-oriented window. For the north-oriented roof window, however, which might be the most relevant to consider for thermal comfort, all combinations of *U*-value and frame investigated are sufficient to meet the target, but full design flexibility could also be within reach by using either the standard frame (B3) in combination with *U*-values below the investigated range or the improved frame (B2) in combination with a *U*-value of 0.7 W/m^2 K.

4. Conclusions and outlook

Considering typical roof and façade window options that provided comfortable and well-lit spaces in all parts of the 1 ½ storey building section considered, maximising solar gains in south-oriented rooms was found to have limited potential for reducing space heating demand at building level. In both climates increasing glazing *g*-value in north-oriented rooms could reduce space heating demand up to several times more than increasing the *g*-value in south-oriented rooms. In north-oriented rooms in Copenhagen, glazing *U*-value had approximately the same saving potential as the *g*-value, while in Rome, the *g*-value was significantly more important than the *U*-value for all room types. Improving thermal properties of roof window frame constructions (including junction between roof and window) from the best level commonly available on the market today (B3), to the level of a state-of the art construction (B2), reduced space heating demand in Copenhagen and Rome, respectively, by two to three and 1−1.5 times more than could be achieved per change in *U*- and *g*-values.

Since maximum g-value is limited either by the technical limitations of the double- or triple energy-glazing considered, or by the risk of overheating, and since increased window size in general does not hold a potential for improving space heating demand, certain thermal properties of glazing and frame are needed to ensure that any part of the building can be designed as comfortable and well-lit spaces, without being critical for achieving nearly zero-energy targets at building level. In Copenhagen, energy conservation targets were met with reasonable flexibility using low-energy triple-glazing with *U*-value 0.5−0.7 W/m^2 K. Standard frame construction (B3) was sufficient in rooms with south-oriented roof windows, while north-oriented roof windows would need frame constructions with significantly better thermal properties than are currently standard practice in order to be considered an independent option for the loft rooms. In Rome, standard frame construction and the range of glazing *U*-value investigated (0.7−1.3 W/m^2 K), was sufficient to meet the targeted space heating demand in all cases.

By considering several combinations of glazing size and transmittances, this paper also points at the possibility of further improving thermal properties of glazing and frame to a level where the choice of transmittances will no longer be critical for nearly zero-energy targets. In general, products with solar control coating (i.e. *g*-values as low as possible compared with the light transmittance) are the products that can maximise daylighting the most in solar-exposed rooms without overheating, even if dynamic solar shading or improved venting strategies would allow larger glazing sizes without reducing the transmittances. Less focus on maximising the *g*-values in solar exposed rooms would open up for the use of such solar control-coated products, and permit the use of a number of existing glazing techniques with low transmittances that could provide larger architectural freedom without overheating in an easy and robust way. In Copenhagen, such flexibility would require considerably lower glazing *U*-values than are state-of-the-art today (at least multi-layer glazing with *U*-value 0.3−0.5 W/m^2 K). Additionally, thermal properties of frame construction would have to be improved to the level of (B2) for south-oriented roof windows and to the ideal level of (B1) for north-oriented roof windows. In Rome, the same flexibility was achieved with glazing *U*-values of approximately 0.7 W/m^2 K and standard frame constructions, but for north-oriented roof windows either thermal properties of glazing or frame would have to be slightly improved. These properties are considerably better than standard practice today, but realistic.

Focusing on windows that are just enough well-insulated to meet the energy target using as high *g*-values as possible, is not a sufficient approach to help increase flexibility regarding window size. Moreover, thermal properties of glazing and frame are the only parameters that are robust even under difficult conditions. For example, if windows are heavily obstructed by the surroundings, useful transmittances are reduced and larger window sizes are needed for sufficient daylighting. The same would be the case if considering buildings with a more difficult room layout for daylighting. For windows to be robust even under such conditions, glazing *U*-values and frame constructions that allow reasonable to full flexibility in the choice of glazing size and transmittances are recommended. Because window solutions that add more energy to the building than they consume are becoming increasingly difficult to achieve, we suggest that instead of continue focusing on maximising solar gains in south-oriented rooms, which does not hold a particularly large saving potential anymore at building level and increases the risk of overheating, focus in future window development should be on reaching insulation levels of glazing and frame that increase the chances that no room types will be critical for the nearly zero-energy targets at building level. In general, it was found that the thermal properties that allowed window sizes to be selected freely in north-oriented rooms using moderate *g*-values, allowed nearly free choice of transmittance and glazing size in south-oriented rooms.

The values reported for thermal properties of glazing and frame in this study, are an outcome of the specific building section considered, which consists of rooms with identical floor plans, modelled as separate spaces with either roof- or façade windows oriented north or south, thus the effect of windows with different slope and orientation in the same room or heat- and air-exchange between zones is not taken into account. More case-specific descriptions of floor plan and user patterns would also affect the results. Furthermore, for the case of Rome, the targeted space heating demand and building insulation level can only be seen as an example of a thinkable nearly zero-energy context. For Copenhagen, however, where targets for nearly zero-energy consumption in residential buildings have been specified, and where the case considered assumes rather ambitious insulation levels, air-tightness and ventilation heat recovery, the thermal properties of glazing and frame suggested in this study may be seen as rather strong indications of a need for glazing U-values of at least state-of-the art level and extensively improved roof window frame constructions.

The present study showed that using the climate-based daylight target suggested by IES [31] for a dwelling with operable windows and moderate venting options, it was possible to achieve thermal comfort according to the ATC model in both a northern and a southern European climate, even without dynamic shading devices or mechanical cooling. Further research on the effect of dynamic solar shading on daylighting and thermal comfort and the achievable venting rates for different building scenarios is needed to determine whether the relatively narrow solution spaces found in south-oriented rooms can be considered acceptable options in terms of indoor climate.

Acknowledgements

The authors would like to thank VELUX A/S for their financial support for this research.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2016.01.038.

References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union, 18/06/2010, Strasbourg, France, 2010.
[2] M.N. Inanici, F.N. Demirbilek, Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey, Build. Environ. 35 (2000) 41–52.
[3] M.-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energ. Build. 38 (2006) 181–188.
[4] L. Vanhoutteghem, S. Svendsen, Modern insulation requirements change the rules of architectural design in low-energy homes, Renew. Energ. 72 (2014) 301–310.
[5] B.P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey, R. Hart, Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities, Sol. Energ. Mater. Sol. Cells 96 (2012) 1–28.
[6] D. Arasteh, H. Goudey, J. Huang, C. Kohler, R. Mitchell, Performance criteria for residential zero energy windows, ASHRAE Trans. 113 (2007) 176–185.
[7] S. Svendsen, J. Kragh, J.B. Laustsen, Energy performance of windows based on the net energy gain, in: Proceedings of the 7th Symposium on Building Physics in the Nordic Countries, June 13, Reykjavik, 2005.
[8] T.R. Nielsen, K. Duer, S. Svendsen, Energy performance of glazing and windows, Sol. Energ. 69 (2001) 137–143.
[9] J. Karlsson, B. Karlsson, A. Roos, A simple model for assessing the energy performance of windows, Energ. Build. 33 (2001) 641–651.
[10] R. Peuhkuri, S. Pedersen, A. Tschui, Principles and specific challenges of very low-energy houses in colder climates and corresponding residential concept houses, in: Presented at the 4th Nordic Passive House Conference, 17–18 October 2011, Helsinki, Finland. NorthPass, 2012, online at: northpass.ivl.se/publicationsfromnorthpass/articles/articles.5.5c577972135ee95b5638000912.html.
[11] A. Gasparella, G. Pernigotto, F. Cappelletti, P. Romagnoni, P. Baggio, Analysis and modelling of window and glazing systems energy performance for a well-insulated residential building, Energ. Build. 43 (2011) 1030–1037.
[12] Robertson, S., Thompson, M. Guidelines for sizing roof windows. WITpress 2006 online at: www.witpress.com/elibrary/wit-transactions-on-the-built-environment/86/16363.
[13] S. Jaber, S. Ajib, Thermal and economic windows design for different climate zones, Energ. Build. 43 (2011) 3208–3215.
[14] P. Ihm, L. Park, M. Krarti, D. Seo, Impact of window selection on the energy performance of residential buildings in South Korea, Energ. Policy 44 (2012) 1–9.
[15] Active House Alliance, Active House–The Specifications for Residential Buildings, 2nd ed., 2013, Brussels, Belgium, Available at: www.activehouse.info/about-active-house/specification.
[16] P. Foldbjerg, T. Asmussen, Using ventilative cooling and solar shading to achieve good thermal environment in a Danish Active House, REHVA Eur. HVAC J. 50 (3) (2013) 36–42.
[17] G.C.J. Skarning, S. Svendsen, C.A. Hviid, Investigation and description of European buildings that may be representative for "nearly zero" energy single family houses in 2020, in: Proceedings of the CISBAT Conference, 4-6 September, Lausanne, 2013, pp. 247–252.
[18] K. Tsikaloudaki, K. Laskos, T. Theodosiou, D. Bikas, The energy performance of windows in Mediterranean regions, Energ. Build. 92 (2015) 180–187.
[19] C.E. Ochoa, M.B.C. Aries, E.J. van Loenen, J.L.M. Hensen, Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, Appl. Energ. 95 (2012) 238–245.
[20] F. Cappelletti, A. Prada, P. Romagnoni, A. Gasparella, Passive performance of glazed components in heating and cooling of an open-space office under controlled indoor thermal comfort, Build. Environ. 72 (2014) 131–144.
[21] J.W. Lee, H.J. Jung, J.Y. Park, J.B. Lee, Y. Yoon, Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements, Renew. Energ. 50 (2013) 522–531.
[22] V. Motuziene, E.S. Juodis, Simulation based complex energy assessment of office building fenestration, J. Civil Eng. Manage. 16 (3) (2010) 345–351.
[23] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energ. Build. 102 (2015) 149–156.
[24] Y.G. Yohanis, B. Norton, A comparison of the analysis of the useful net solar gain for space heating, zone-by-zone and for a whole-building, Renew. Energ. 19 (2000) 435–442.
[25] W. O'Brian, A. Athienitis, T. Kesik, Thermal zoning and interzonal airflow in the design and simulation of solar houses: a sensitivity analysis, J. Build. Perform. Sim. 4 (2011) 239–256.
[26] US Department of Energy, EnergyPlus Energy simulation software, ht***tp://ap***ps1.eere.en***ergy.g***ov/buildings/energyplus/ (accessed 15.07.15).
[27] European standard EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. CEN.
[28] S.O. Aggerholm, K.E. Grau, SBi-anvisning 213: Bygningers energibehov–Beregningsvejledning, 3rd ed., Danish Building Research Institute, Aalborg University, 2014 (in Danish).
[29] J. Mardaljevic, J. Christoffersen, A roadmap for upgrading national/EU standards for daylight in buildings, in: Proceedings of the CIE Centenary Conference, 15–16 April, Paris, 2013, pp. 178–187.
[30] M. Andersen, J. Mardaljevic, S.W. Lockley, A framework for predicting the non-visual effects of daylight–Part I: photobiology-based model, Light. Res. Technol. 44 (2012) 37–53.
[31] IESNA, LM-83-12, IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York, NY, USA, IESNA Lighting Measurement, 2012.
[32] DAYSIM, Advanced daylight simulation software. ht***tp://da***ysi***m.n***ing.com/ (accessed 15.07.15).
[33] Y. Zhang, I. Korolija, Performing complex parametric simulations with jEPlus, in: SET2010-9th International Conference on Sustainable Energy Technologies, 24–27 August, Shanghai, China, 2010.
[34] Y. Zhang, 'Parallel' EnergyPlus and the development of a parametric analysis tool, in: IBPSA BS2009, 27-30 July, Glasgow, UK, 2009.

[35] Arasteh, D., Kohler, C., Griffith, B. Modeling Windows in Energy Plus with Simple Performance Indices. Report LBNL-2804E, Lawrence Berkeley National Laboratory, October 2009.
[36] U.S. Department of Energy, EnergyPlus Engineering reference. Published online 2014. Available at: ht***tp://ap***ps1.eere.en***ergy.g***ov/buildings/energyplus/pdfs/engineeringreference.pdf.
[37] Jensen, J.M., Lund, H., Design Reference Year, DRY - et nyt dansk reference år. Technical Report lfv-281, Technical University of Denmark, 1995 (in Danish).
[38] Glasfakta 2012: Et praktisk hjælpemiddel for valg af bygningsglas. Pilkington Danmark A/S, Denmark, 2012 (in Danish).

Paper 4

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

G.C.J. Skarning, C.A. Hviid and S. Svendsen

Published in: *Energy & Buildings 135 (2017) 302-311*

Energy and Buildings 135 (2017) 302–311

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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

Gunnlaug Cecilie Jensen Skarning*, Christian Anker Hviid, Svend Svendsen

Technical University of Denmark, Department of Civil Engineering, Brovej, Building 118, Kgs. Lyngby DK-2800, Denmark

ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form
22 November 2016
Accepted 24 November 2016
Available online 27 November 2016

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

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.

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

* Corresponding author.
E-mail addresses: gujs@byg.dtu.dk, gunnlaug_cecilie@yahoo.no (G.C.J. Skarning).

http://dx.doi.org/10.1016/j.enbuild.2016.11.053

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°-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 façade 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.

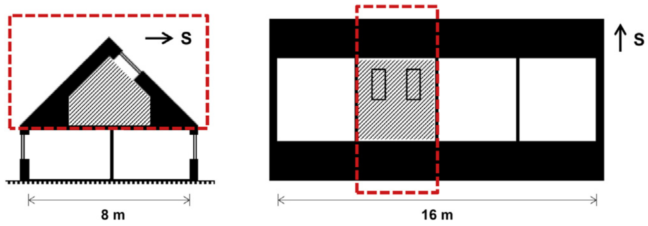


Fig. 1. Sketch indicating the location of the loft room in the middle part of a 1½-storey single-family house with simplistic floor plan: Vertical section of the house to the left and horizontal section of the 1st floor to the right.

Table 1
Building specifications for the thermal simulation model.

	Rome	Copenhagen
Roof construction		
U-value[a] (W/m² 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

[a] Includes linear heat losses.

2. Methodology

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

The study considered a loft room with floor dimensions of 4 × 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 (Fig. 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°-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 Fig. 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.

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

		GlazingU-value(W/m² K)	Frame properties				
			Width (m)	U-value (W/m² K)	Psi g (W/m K)	Psi w (W/m K)	Specific heat loss[a] (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

[a] 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 m by 1.48 m.

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.

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 (Sections 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/m² [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/m² 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/m² 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 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 1300 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 h 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 Fig. 2) to systematise and illustrate the results.

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.

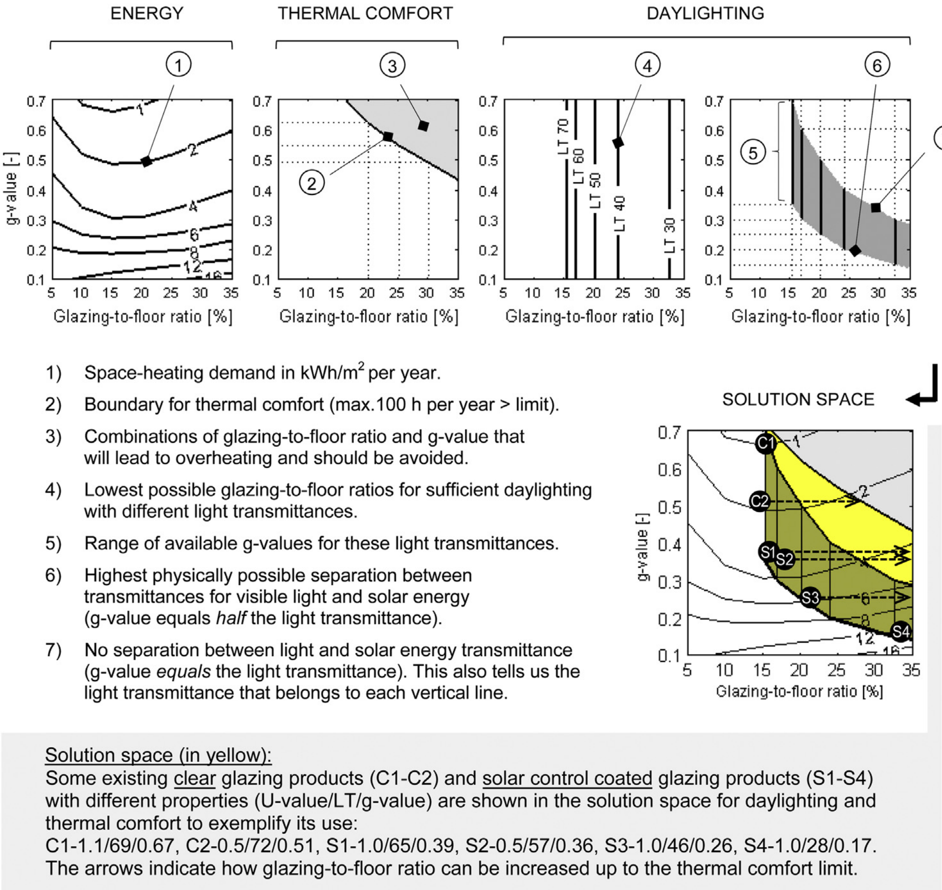


Fig. 2. Reader's guide to the glazing diagram.

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[a] (%)	5	5
	10	10
	15	15
	20	20
	25	25
	30	30
	35	35
Glazing g-value (−)	0.1	0.1
	0.2	0.2
	0.3	0.3
	0.4	0.4
	0.5	0.5
	0.6	0.6
	0.7	0.7
Light transmittance (%)	10[b]	10[b]
	20[b]	20[b]
	30	30
	40	40
	50	50
	60	60
	70	70

[a] 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.
[b] 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 Fig. 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 h 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 (Sections 3.1 and 3.2). For

Table 4
Minimum glazing-to-floor ratio for daylighting with LT 70% for various shading factors with the set-point of 300 W/m² 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

more examples of its use is referred to the papers by Vanhoutteghem et al. [17] and Skarning, Hviid & Svendsen [18].

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/m² 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/m² 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

Fig. 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.

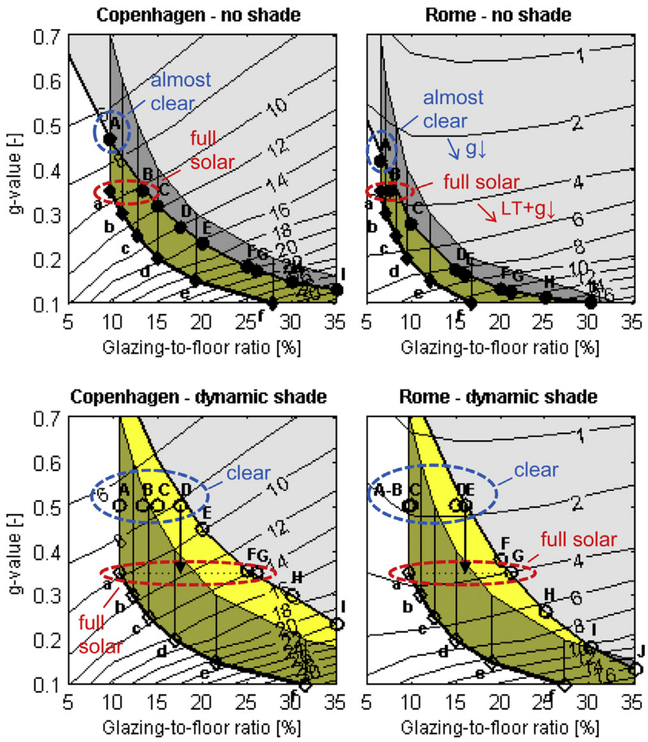


Fig. 3. Comparison of solution spaces with no additional shading device (top) and using an external dynamic shading device (bottom). Illustrated for roof windows with standard thermal properties (see Table 2) in Copenhagen (left) and Rome (right). The evaluation points A–J and a–f are used for comparison 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 Fig. 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.

Figs. 4 and 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. Max-

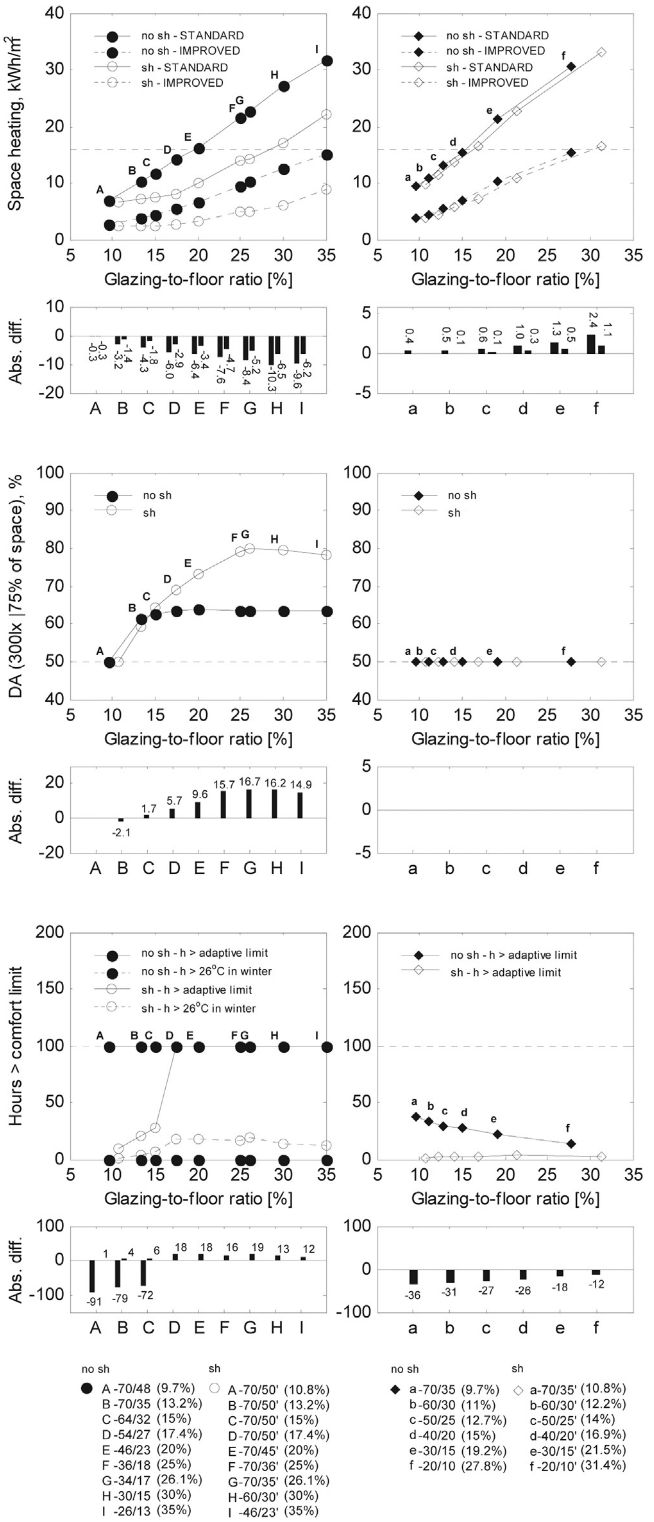


Fig. 4. Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading in Copenhagen for the evaluation points A–I (left) and a–f (right). LT, g-value and glazing-to-floor ratio of the evaluation points are listed in the bottom of the figure.

imum 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 Fig. 3, bottom row). Moreover, LT, g-value and glazing-to-floor ratio of each evaluation point can be found in the bottom of Figs. 4 and 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 Fig. 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 Fig. 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 Fig. 3, bottom row). Comparison of the space-heating demand with and without dynamic shading for point A in Figs. 4 and 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 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 (Fig. 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 Fig. 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 (Figs. 4 and 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

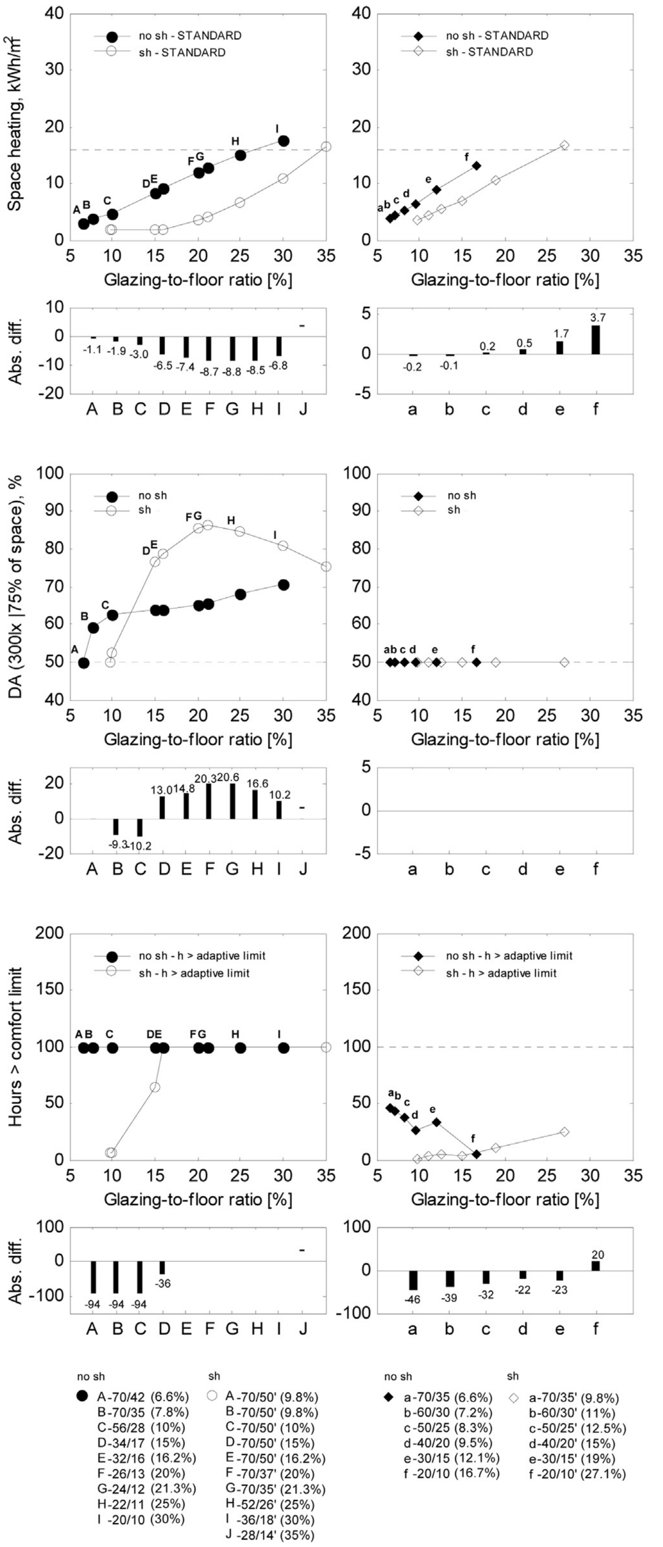


Fig. 5. Comparison of energy, daylighting and thermal comfort achievements with and without dynamic shading in Rome for the evaluation points A–J (left) and a–f (right). LT, g-value and glazing-to-floor ratio of the evaluation points are listed in the bottom of the figure.

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.

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 Fig. 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 Fig. 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 Figs. 4 and 5).

The use of dynamic solar shading in combination with clear glazing (see the options referred to as ‘clear’ in Fig. 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 Figs. 4 and 5).

Finally, the use of dynamic shading in combination with optimal solar-control coating (see the options referred to as ‘full solar’ in Fig. 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 Figs. 4 and 5).

In Copenhagen options with dynamic shading on the comfort limit led to around 20 h with operative temperatures above 26 °C in the winter season (see points D–J, Fig. 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

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 Fig. 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)

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 Fig. 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 Fig. 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 h less exceeding the comfort limit with dynamic shading than without (see point C in Figs. 4 and 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 Figs. 4 and 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 h or increase the time with sufficient daylighting by 750–1000 h 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 h 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.

Acknowledgement

The authors would like to thank VELUX A/S for their financial support for this research.

References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union, 18/06/2010, Strasbourg, France, 2010.
[2] M.-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energy Build. 38 (2006) 181–188.
[3] R. Marsh, V.G. Larsen, M. Kragh, Housing and energy in Denmark: past, present, and future challenges, Build. Res. Inf. 38 (1) (2010) 92–106.
[4] T.S. Larsen, R.L. Jensen, Measurements of energy performance and indoor environmental quality in 10 Danish passive houses – a case study, Proc. Healthy Build. (2009) (September 13–17 2009) Syracuse, USA.
[5] C. Brunsgaard, M.-A. Knudstrup, P. Heiselberg, Occupant experience of everyday life in some of the first passive houses in Denmark, Hous. Theory Soc. 29 (2012) 223–254.
[6] P. Foldbjerg, T. Asmussen, Using ventilative cooling and solar shading to achieve good thermal environment in a Danish active house, REHVA Eur. HVAC J. 50 (3) (2013) 36–42.
[7] S. Petersen, Daylight conditions and thermal indoor climate in low-energy homes –the consequence of Danish building code, in: Proceedings of 7th Passivhus Norden, Sustainable Cities and Buildings, Copenhagen, 20–21 August, 2015.
[8] A. Mavrogianni, M. Davies, J. Taylor, Z. Chalabi, P. Biddulph, E. Oikonomou, P. Das, B. Jones, The impact of occupancy patterns: occupant-controlled ventilation and shading on indoor overheating risk in domestic environments, Build. Environ. 78 (2014) 183–198.
[9] J. Apte, D. Arasteh, Y.J. Huang, Future Advanced Windows for Zero-Energy Homes. ASHRAE Transactions 109 Part 2 (2003). Lawrence Berkeley National Laboratory Report LBNL-51913.
[10] F. Gugliermetti, F. Bisegna, Saving energy in residential buildings: the use of fully reversible windows, Energy 32 (7) (2007) 1235–1247.
[11] P. Ihm, L. Park, M. Krarti, D. Seo, Impact of window selection on the energy performance of residential buildings in South Korea, Energy Policy 44 (2012) 1–9.
[12] A. Gasparella, G. Pernigotto, F. Cappelletti, P. Romagnoni, P. Baggio, Analysis and modelling of window and glazing systems energy performance for a well-insulated residential building, Energy Build. 43 (2011) 1030–1037.
[13] Active House Alliance. Active House – The Specifications for Residential Buildings. 2nd edition, Brussels, Belgium, 2013. Available at: www.activehouse.info/about-active-house/specifications/.
[14] European standard EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. CEN.
[15] L. Vanhoutteghem, S. Svendsen, Modern insulation requirements change the rules of architectural design in low-energy homes, Renew. Energy 72 (2014) 301–310.
[16] G.C.J. Skarning, S. Svendsen, C.A. Hviid, Investigation and description of European buildings that may be representative for nearly zero energy single family houses in 2020, in: Proceedings of the CISBAT Conference, Lausanne, 4–6 September, 2013, pp. 247–252.
[17] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energy Build. 102 (2015) 149–156.
[18] G.C.J. Skarning, C.A. Hviid, S. Svendsen, Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe, Energy Build. 116 (2016) 602–613.
[19] C. du Montier, A. Potvin, C.M.H. Demers, Adaptive façades for architecture: energy and lighting potential of movable insulation panels, in: Proceedings of the 29th PLEA Conference, Sustainable Architecture for a Renewable Future, Munich, Germany September, 2013, pp. 10–12.
[20] F. Favoino, M. Overend, Q. Jin, The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies, Appl. Energy 156 (2015) 1–15.
[21] M.-C. Dubois, K. Grau, S. Traberg-Borup, K. Johnsen, Impact of Three Window Configurations on Daylight Conditions: Simulations with Radiance By og Byg Documentation 047, Danish Building and Urban Research, Hørsholm, Denmark, 2003.
[22] V. Motuziene, E.S. Juodis, Simulation based complex energy assessment of office building fenestration, J. Civil Eng. Manage. 16 (3) (2010) 345–351.
[23] D. Appelfeld, A. McNeil, S. Svendsen, An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems, Energy Build. 50 (2012) 166–176.
[24] S. Grynning, B. Time, B. Matusiak, Solar shading control strategies in cold climates – Heating, cooling demand and daylight availability in office spaces, Sol. Energy 107 (2014) 182–194.
[25] H. Poirazis, Å. Blomsterberg, M. Wall, Energy simulations for glazed office buildings in Sweden, Energy Build. 40 (2008) 1161–1170.
[26] F. Gugliermetti, F. Bisegna, Visual and energy management of electrochromic windows in Mediterranean climate, Build. Environ. 38 (3) (2003) 479–492.
[27] R. Sullivan, E.S. Lee, M.D. Rubin, S.E. Selkowitz, The energy performance of electrochromic windows in heating-dominated geographic locations, in: Proceedings of the SPIE International Symposium on Optical Materials Technology for Energy Efficiency & Solar Energy Conversion XV, 16–19 September, Freiburg, Germany, 1996 (Lawrence Berkeley Laboratory Report LBL-38252).
[28] R. Johnson, R. Sullivan, S. Selkowitz, S. Nozaki, C. Conner, D. Arasteh, Glazing energy performance and design optimization with daylighting, Energy Build. 6 (1984) 305–317.
[29] Y. Huang, J.-L. Niu, T.-M. Chung, Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates, Appl. Energy 134 (2014) 215–228.
[30] M.V. Nielsen, S. Svendsen, L.B. Jensen, Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Sol. Energy 85 (2011) 757–768.
[31] A.A.Y. Freewan, Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions, Sol. Energy 102 (2014) 14–30.
[32] A. Tzempelikos, H. Shen, Comparative control strategies for roller shades with respect to daylighting and energy performance, Build. Environ. 67 (2013) 179–192.
[33] A. Atzeri, F. Cappelletti, A. Gasparella, Internal versus external shading devices performance in office buildings, Energy Procedia 45 (2014) 463–472.
[34] R. Singh, I.J. Lazarus, V.V.N. Kishore, Effect of internal woven roller shade and glazing on the energy and daylighting performances of an office building in the cold climate of Shillong, Appl. Energy 159 (2015) 317–333.
[35] M. David, M. Donn, F. Garde, A. Lenoir, Assessment of the thermal and visual efficiency of solar shades, Build. Environ. 46 (2011) 1489–1496.
[36] H. Shen, A. Tzempelikos, A.M. Atzeric, A. Gasparella, F. Cappelletti, Dynamic commercial façades versus traditional construction: energy performance and comparative analysis, J. Energy Eng. 141 (4) (2015) 04014041.
[37] E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office, Energy Build. 29 (1998) 47–63.
[38] E. Lee, A. Tavil, Energy and visual comfort performance of electrochromic windows with overhangs, Build. Environ. 42 (6) (2007) 2439–2449.
[39] F. Goia, Y. Cascone, The impact of an ideal dynamic building envelope on the energy performance of low energy office buildings, Energy Procedia 58 (2014) 185–192.
[40] G. Yun, K.C. Yoon, K.S. Kim, The influence of shading control strategies on the visual comfort and energy demand of office buildings, Energy Build. 84 (2014) 70–85.
[41] D. Arasteh, H. Goudey, J. Huang, C. Kohler, R. Mitchell, Performance criteria for residential zero energy windows, ASHRAE Trans. 113 (2007) 176–185.
[42] S. Firląg, M. Yazdanian, C. Curcija, C. Kohler, S. Vidanovic, R. Hart, S. Czarnecki, Control algorithms for dynamic windows for residential buildings, Energy Build. 109 (2015) 157–173.
[43] W. O'Brian, A. Athienitis, T. Kesik, Thermal zoning and interzonal airflow in the design and simulation of solar houses: a sensitivity analysis, J. Build. Perform. Simul. 4 (2011) 239–256.
[44] K. Tsikaloudaki, Th. Theodosiou, K. Laskos, D. Bikas, Assessing cooling energy performance of windows for residential buildings in the Mediterranean zone, Energy Convers. Manage. 64 (2012) 335–343.
[45] G. Kim, H.S. Lim, T.S. Lim, L. Schaefer, J.T. Kim, Comparative advantage of an exterior shading device in thermal performance for residential buildings, Energy Build. 46 (2012) 105–111.
[46] A.A.E.-M.M. Ali Ahmed, Using simulation for studying the influence of vertical shading devices on the thermal performance of residential buildings (case study: new Assiut City), Ain Shams Eng. J. 3 (2012) 163–174.
[47] J. Karlsson, B. Karlsson, A. Roos, Control strategies and energy saving potentials for variable transmittance windows versus static windows, in: Proceedings of Eurosun, 19–22 June, Copenhagen, Denmark, 2000.
[48] R. Sullivan, F. Beck, D. Arasteh, W. Selkowitz, Energy Performance of Evacuated Glazings in Residential Buildings. Report LBL-37130, Lawrence Berkeley Laboratory, 1995.
[49] J.H. Klems, Net energy performance measurements on electrochromic skylights, Energy Build. 33 (2001) 93–102.
[50] J. Du, Window systems and energy performance in one-family houses: size and shading effects, in: Proceedings of the Building Simulation and Optimization Conference, London, 23–24 June, 2014.

[51] J. Du, B. Hellström, M.-C. Dubois, Daylighting Utilization in the Window Energy Balance Metric: Development of a Holistic Method for Early Design Decisions, Lund University, 2014.
[52] J. Yao, N. Zhu, Evaluation of indoor thermal environmental: energy and daylighting performance of thermotropic windows, Build. Environ. 49 (2012) 283–290.
[53] N. DeForest, A. Shehabi, J. O'Donnell, G. Garcia, J. Greenblatt, E.S. Lee, S. Selkowitz, D.J. Milliron, United States energy and CO2 savings potential from deployment of near-infrared electrochromic window glazings, Build. Environ. 89 (2015) 107–117.
[54] S. Carlucci, G. Cattarin, F. Causone, L. Pagliano, Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II), Energy Build. 104 (2015) 378–394.
[55] S.O. Aggerholm, K.E. Grau, SBi-anvisning 213: Bygningers Energibehov —Beregningsvejledning, 3rd edition, Danish Building Research Institute, Aalborg University, Danish, 2014.
[56] US Department of Energy, EnergyPlus Energy simulation software, http://apps1. eere.energy.gov/buildings/energyplus/ (Accessed 15 July 2015).
[57] J.M. Jensen, H. Lund, Design Reference Year, DRY — et nyt dansk referenceår Technical Report lfv-281, Technical University of Denmark, Danish, 1995.
[58] Danish Transport and Construction Agency, Building Regulations 2015 Ver. 01.07.2016, 2016, http://bygningsreglementet.dk/br15_01/0/42 (Accessed 20 August 2016) (in Danish).
[59] J. Mardaljevic, J. Christoffersen, A roadmap for upgrading national/EU standards for daylight in buildings, in: Proceedings of the CIE Centenary Conference, Paris, 15–16 April, 2013, pp. 178–187.
[60] J. Mardaljevic, J. Christoffersen, Climate connectivity' in the daylight factor basis of building standards, Build. Environ. (2016) (Article in press).
[61] A.R. Webb, Considerations for lighting in the built environment: non-visual effects of light, Energy Build. 38 (7) (2006) 721–727.
[62] IESNA, LM-83-12, IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), IESNA Lighting Measurement, New York, NY, USA, 2012.
[63] Y. Zhang, I. Korolija, Performing complex parametric simulations with jEPlus, in: SET2010 — 9th International Conference on Sustainable Energy Technologies, 24–27 August, Shanghai, China, 2010.
[64] Y. Zhang, 'Parallel' EnergyPlus and the development of a parametric analysis tool, in: IBPSA BS2009, 27–30 July 2009, Glasgow, UK, 1382–1388.
[65] DAYSIM, Advanced daylight simulation software. http://daysim.ning.com/ (Accessed 15 July 2015).

Paper 5

"The cost efficiency of improved roof windows in two well-lit nearly zero-energy houses in Copenhagen"

G.C.J. Skarning, C.A. Hviid and S. Svendsen

Published in: *Energy & Buildings 140 (2017) 399-417*

Energy and Buildings 140 (2017) 399–417

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

The cost efficiency of improved roof windows in two well-lit nearly zero-energy houses in Copenhagen

Gunnlaug Cecilie Jensen Skarning*, Christian Anker Hviid, Svend Svendsen

Technical University of Denmark, Department of Civil Engineering, Brovej, Building 118, Kgs. Lyngby DK-2800, Denmark

ARTICLE INFO

Article history:
Received 27 June 2016
Received in revised form
18 November 2016
Accepted 26 January 2017
Available online 4 February 2017

Keywords:
Roof windows
Cost-effectiveness
Window design
Glazing
Frame
Solar-control coating
Space heating
Climate-based daylighting
Adaptive thermal comfort

ABSTRACT

Roof windows are efficient and flexible daylight sources that are essential in certain types of houses if they are to achieve sufficient daylighting throughout. Previous studies have indicated that, for such buildings to meet nearly zero-energy targets in an easy and robust way without compromising on daylighting and thermal comfort, the thermal properties of roof window glazing, frames and junctions need to be considerably improved. However, the barriers to improving roof windows to levels above the current best standard practice remain great so long as we do not know the economic benefits of such improvements. The aim of this study was to quantify the scope for investing in improved roof window solutions in buildings insulated to consume nearly zero-energy. Based on two single-family houses in Copenhagen with typical roof windows and adequate daylighting, the study identified the prices at which various types of roof window improvements would have to be made available to achieve the same cost efficiency as improved insulation. If the improvements can be made available for less than these prices, the installation of improved roof windows would make it cheaper to construct well-lit and comfortable nearly zero-energy homes.

1. Introduction

With the recast of the Energy Performance of Buildings Directive adopted in 2010 [1], all new buildings in the European Union are required to consume nearly zero-energy by the end of 2020. This creates a strong need for research in technologies and solutions that can not only provide sufficient daylighting and thermal comfort in homes but also meet the ambitious energy requirements in a cost-efficient way.

Previous studies on the energy performance of windows in well-insulated residential buildings [2–5] have indicated that the degree to which solar gains can be utilised decreases with space-heating demand. Furthermore, studies on the impact of various window parameters on energy, daylighting and thermal comfort in rooms insulated to nearly zero-energy levels [6,7] have shown that the thermal properties of windows are becoming increasingly important if nearly zero-energy targets are to be met in a reasonably robust and flexible way without compromising on sufficient daylighting and thermal comfort. This is especially true of roof windows in northern European climates. An earlier study by the present authors [7] on individual rooms in a 1½-storey single-family house with a simplified floor plan identified the need for considerably better thermal properties in glazing, frames, and junctions than are current best standard practice. Roof windows are efficient and flexible daylight sources that are essential in certain types of houses if they are to achieve sufficient daylighting throughout. However, the large convection heat losses due to their slope and the problems in reducing heat loss through junctions between roof and window mean that roof windows still have a lot more scope for improvement than façade windows.

While more and more insulation is being inserted in the building envelope to comply with the increasing requirements for space heating, a lack of knowledge is still preventing roof windows with considerably improved thermal properties from being made commonly available and installed. Doubt about the economic benefits and scope for investing in such improvements may be one of the barriers. With the large insulation thicknesses needed in the building envelope to consume nearly zero energy, however, the costs of compensating for building components that are not optimised for the new conditions by means of insulation have increased significantly. It is therefore likely that we are about to reach a situation in which a new generation of considerably improved roof windows need to be made available to ensure a reasonably cost-optimal choice of basic building components.

* Corresponding author.
E-mail addresses: gujs@byg.dtu.dk, gunnlaug_cecilie@yahoo.no (G.C.J. Skarning).

http://dx.doi.org/10.1016/j.enbuild.2017.01.080
0378-7788/

1.1. Aim of study

The hypothesis behind this study was that roof windows with considerably improved thermal properties compared to what is currently best standard practice would make the construction of nearly zero-energy homes with sufficient daylighting and thermal comfort more cost-efficient. However, any attempt to determine the cost efficiency of various improvements directly by means of common economic evaluation techniques [8,9] would require qualified cost estimations for roof window products that do not yet exist or are not yet commonly produced. The use of such techniques would therefore be of limited purpose in this case. Instead this study took a different approach, where the aim was to quantify the scope for investing in improved roof windows. In the Danish Building Code [10,11], a fixed requirement for the maximum energy use permitted in nearly zero-energy residential buildings has already been defined, and from 2020 all new houses will have to comply with this requirement in one way or another. This made it possible to establish a measure of the scope for investing in improved roof window by holding the energy saving potential of various types of roof window improvements up against the cost of saving the required energy by current means. Given that a building has the best high-end practice façade windows currently available and that all other building components affecting the space-heating demand have been optimised to nearly ideal levels, the amount of insulation inserted in the building envelope is the parameter that would most likely be used to compensate for the performance of the roof windows. For two new single-family houses in Denmark with typical use of roof windows, we therefore investigated how much less insulation building owners would need in the houses to comply with Danish Building Regulations if they installed various types of improved roof windows instead of the options that are currently the best standard practice. The cost of this amount of insulation not needed can then be seen as a measure of the scope for investing in improved roof windows. It will be up to the manufacturers to determine the prices at which the various types of improved roof windows can be made available. However, if the improvements (including the replacements needed within a time frame corresponding to the lifetime of insulation) can be made available at prices that are less than the savings in insulation costs identified throughout this paper, near future energy requirements could be met in a cheaper and more cost-effective way than by using so much insulation.

1.2. Literature review

For façade windows, Jaber and Ajib [12] and Karabay and Arici [13] have examined the cost-optimal selection of glazing using common economic evaluation techniques requiring cost estimation inputs. As part of a study by Hansen and Vanhoutteghem [14] on the economic optimisation of new low-energy homes, the cost-effectiveness of existing windows has also been evaluated in relation to other building components. For roof windows, however, very few studies could be found that consider their performance in very well-insulated homes. Studies by Foldbjerg and Asmussen [15], Du et al. [16] and Du [17] have investigated the effect of existing roof windows on energy, daylighting and thermal comfort in well-insulated residential buildings, but none of these studies examined the economic effect of improving roof windows to levels beyond the currently best standard practice. By doing so, the present study contributes to new knowledge within the field.

2. Methodology

The study considered two large single-family houses, in which approximately one third of the floor area depends on roof windows for sufficient daylighting:

Table 1
Thermal key parameters and system specifications for the two houses.

	Case A	Case B
Building size		
Gross floor area (m^2), wall thicknesses of 0.4 m	213	213
Internal floor area (m^2)	190	190
Transmission area (inner dimensions)[a]		
Walls (m^2), before subtracting windows	137 (151)	138 (187)
Roof (m^2), before subtracting windows	153 (179)	190 (213)
Ground floor (m^2)	108 (126)	190 (213)
Total transmission area per internal floor area (–)	2.1	2.7
Cold bridge lengths (inner dimensions)		
Foundation (m), psi = 0.15 W/m K	44	55
Other junctions (m), psi = 0.05 W/m K	75	65
System properties and internal loads[b]		
Heating set point (°C)	20	20
Venting set point (°C)	23	23
Infiltration rate (h^{-1})	0.05	0.05
Maximum venting rate (h^{-1})	3 (+ 6 and 9)	3 (+ 6 and 9)
Mechanical ventilation rate (h^{-1})	0.6	0.6
Efficiency of heat recovery (–)	0.9	0.9
Internal loads, including lighting (W/m^2)	5	5

[a] The surface areas used for calculation of insulation costs are shown in brackets. These assume construction thicknesses of 0.4 m for walls and 0.7 m for roofs irrespective of insulation level.
[b] Internal loads and ventilation rates were inserted based on the internal floor area of the zones and air change rates assume a room height of 2.5 m in all zones.

- Case A – a 1½-storey house with 45° sloped roof windows on the 1st floor.
- Case B – a one-storey quadratic house with horizontal roof windows in the core area.

Figs. 1 and 2 show the floor plans, key dimensions, and room types in each thermal zone for the two houses. In both houses, we assumed air-tight building envelopes with construction details of high quality and the best available heat recovery efficiency for ventilation, etc. (see Table 1). It should be noted that Case A is a considerably more compact type of house than Case B (see the transmission areas in Table 1), while both houses are considerably more compact than the long and narrow one-storey single-family houses with only façade windows commonly found in Denmark.

The overall methodology of the study is sketched in Fig. 3. As indicated in the figure, a reference scenario with the best high-end practice façade windows currently available and the best standard-practice roof windows currently available was first established for the two houses (see REF in Tables 2 and 3). This scenario was set up for sufficient daylighting and thermal comfort based on knowledge from previous studies on roof and façade windows at room level [6,7], following the procedure described in Section 2.2, and daylighting was tested through simulation. Furthermore, to make it possible to see how the findings depend on the space-heating demand of the reference, each house was insulated to comply with three different targets for space-heating demand, where the best corresponds to Danish requirements for nearly zero-energy consumption (see Section 2.1.1). This was done following the procedure described in Section 2.3. Then, the thermal comfort for the

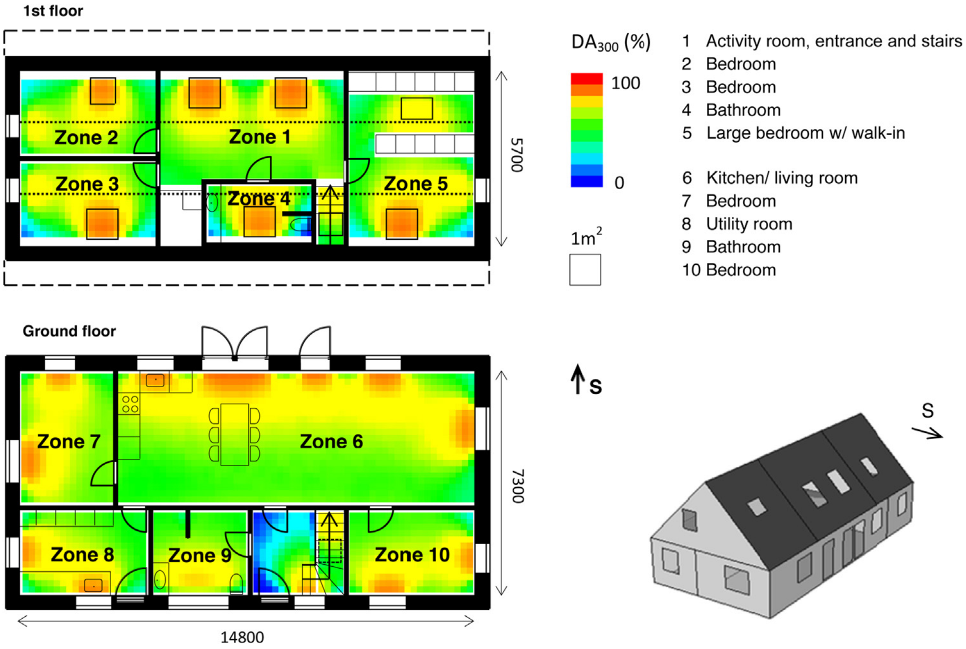


Fig. 1. Plan drawing for Case A with daylight distribution for the reference scenario, shown as percentage of daylight hours with illuminances of at least 300 lx in the sensor points.

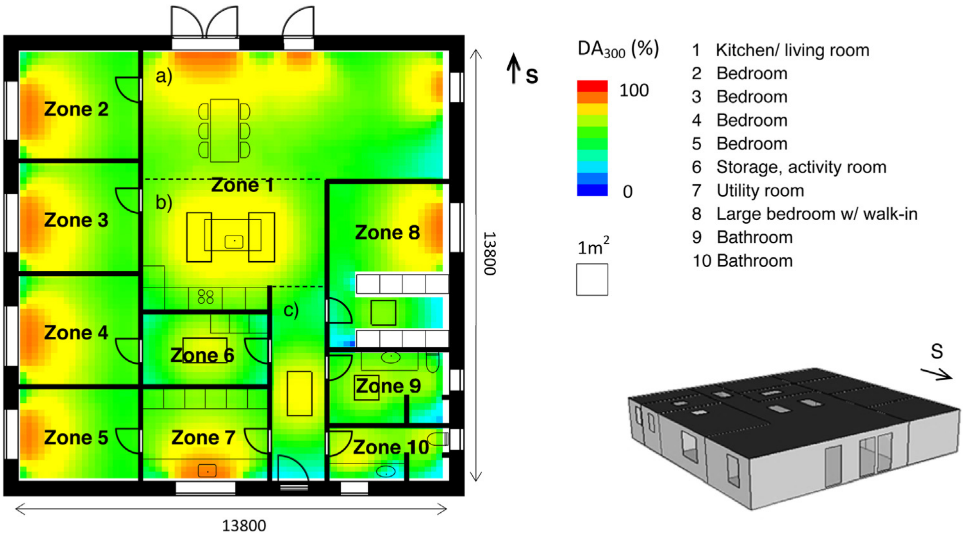


Fig. 2. Plan drawing for Case B with daylight distribution for the reference scenario, shown as percentage of daylight hours with illuminances of at least 300 lx in the sensor points.

reference scenario was checked (see Section 2.4), before the effect of replacing the standard-practice roof windows in the reference scenario with various types of roof window improvements was investigated. The façade windows were kept the same.

These investigations consisted of the following two parts (Fig. 3):

(1) A part showing the effect of changes to the individual glazing parameters, one at a time. The parameter variations in this part were carried out based on two scenarios similar to the reference scenario, but where the solar energy transmittance (*g*-value) of all roof window glazing corresponded to either no solar control (*g*-value as high as possible) or nearly ideal solar control (*g*-value as low as possible without reducing the light transmittance of the glazing). From this part, it should be possible to estimate the energy saving potential of an arbitrary improvement consisting of small changes in the parameters combined or changes in one single parameter alone. Furthermore, the scope for investing in improvements with small energy saving potentials can be estimated by multiplying these saving potentials by the cost of saving 1 kWh/m^2 by means of insulation for the reference scenario (see Section 2.6.1).

(2) A part showing the effect of a number of specific examples of improved roof windows #A–E (see Tables 2 and 3 and Section 2.5). For these options, the scope for investment was determined directly based on the cost of the insulation no longer needed to achieve an acceptable space-heating demand after installing the improved windows (see Section 2.6.2).

Where any change to the roof windows affected the light transmittance (LT) of the glazing, the glazing size was adjusted to maintain sufficient daylighting.

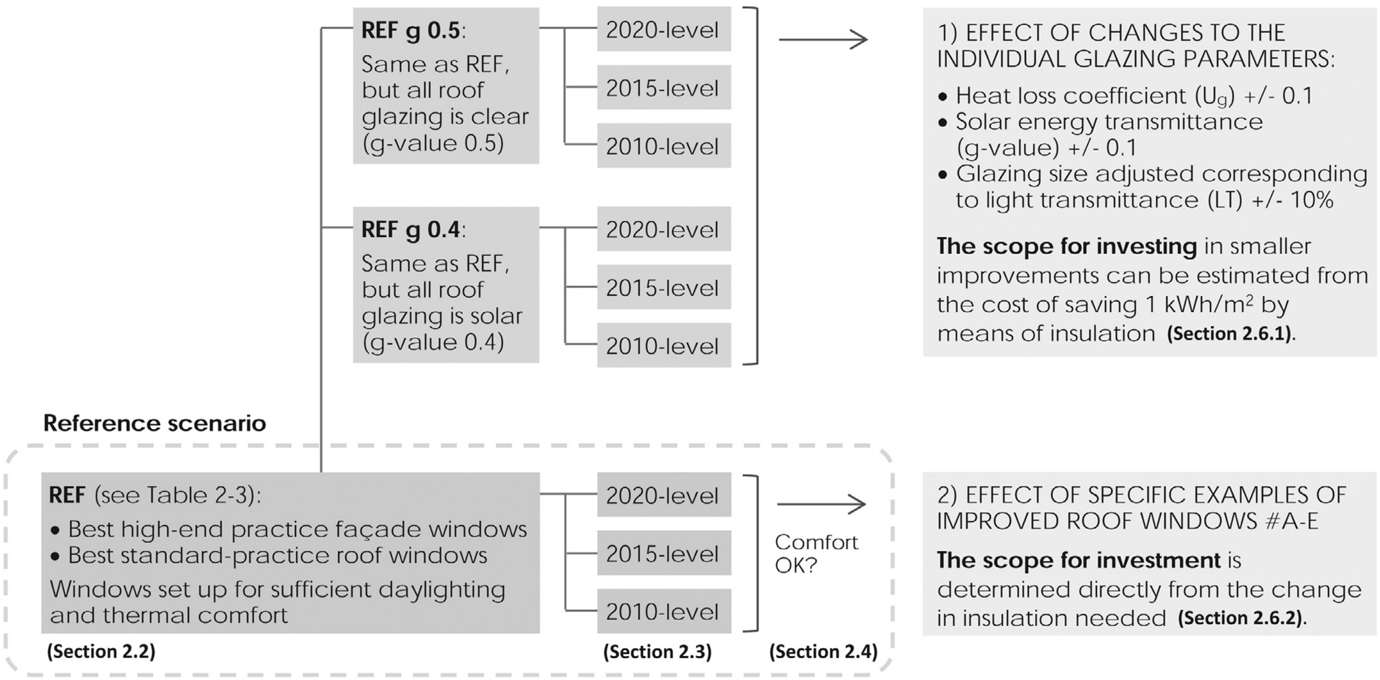


Fig. 3. Overview of the methodology. The left-hand side shows the scenarios used as a basis for carrying out the two investigations on the roof windows, which are shown on the right-hand side. The 'reference scenario' is the basis for the second investigation, while two variations of the reference scenario are the basis for the first investigation. All scenarios were insulated to comply with three different energy requirements, before carrying out the investigations.

Finally, the effect of increasing window sizes to more than needed for sufficient daylighting and the robustness of the scope for investment to changes in the reference scenario were briefly addressed.

Space-heating demand and operative temperatures were simulated using EnergyPlus [18] in combination with the tool jEPlus [19,20] for automated parametric analysis, while daylighting for the reference scenario was tested using the RADIANCE-based daylighting analysis tool DAYSIM [21]. Matlab was used for post-processing of simulation outputs, and further modelling assumptions can be found in Section 2.7. Section 2.1 specifies the performance parameters and criteria used.

2.1. *Performance parameters and evaluation criteria*

In Danish homes, mechanical cooling is normally not installed and electricity consumption for lighting is not part of the requirement for acceptable energy use. So for residential buildings in Denmark, the main variable defining the energy usage is the space-heating demand (Section 2.1.1), while daylighting and thermal comfort are evaluated based on separate criteria (Sections 2.1.2 and 2.1.3).

2.1.1. *Targeted space-heating demands*

According to the nearly zero-energy requirements for residential buildings that will apply in Denmark from 2020 [11], the annual primary energy usage for covering space heating, domestic hot water, and electricity for pumps and ventilation is defined as no more than 20 kWh/m^2, where the primary energy factors are 0.6 for district heating and 1.8 for electricity. For the two houses considered, this leaves a final energy usage for space heating of no more than approximately 12 kWh per m^2 gross floor area per year. Two less ambitious space-heating targets (see Table 4 and Fig. 4) were similarly established based on Danish energy requirements for residential buildings from 2010 and 2015.

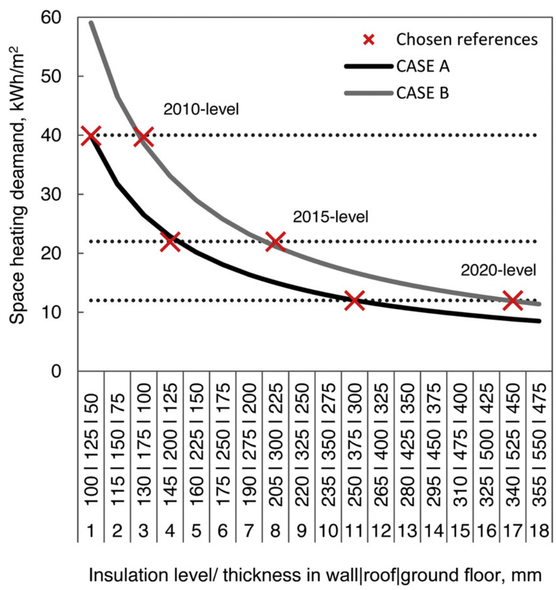


Fig. 4. Space-heating demand as a function of insulation level for the reference scenario, showing the insulation levels needed in the houses to comply with the three energy requirements.

2.1.2. *Evaluation of thermal comfort*

The Adaptive Thermal Comfort (ATC) model in EN 15251 [22] was used to evaluate thermal comfort. Given that occupants are free to use windows for venting, adjust their clothing, and adapt to indoor conditions in other ways, this model states that the comfortable operative temperature is a function of the running mean outdoor air temperature at the location. The upper limit for thermal comfort is therefore not a fixed temperature, but a variable temperature that depends on recent temperatures outdoors. For this study, too much discomfort (or 'overheating') was deemed to have occurred when operative temperatures (T_o) in a zone exceeded the

Table 2
Properties of glazing, frame and junctions for the reference roof and façade windows (REF) and for the five examples of roof window improvements (#A–E) investigated – Case A.

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients[c]		**Total window area**[d]
			U_g 45° (W/m^2 K)	U_g 90° (W/m^2 K)	*g*-value[a] (–)	LT (%)	Width (m)	U_f (W/m^2 K)	Psi g (W/m K)	Psi w (W/m K)	Specific heat loss[b] (W/K)	U'_w (W/m^2 K)	U'_g (W/m^2 K)	A_{win} (m^2)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.92	32.3
Roof	REF	Best standard practice	0.73	0.71	0.39* (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	13.2
	#A	Higher *g*-value	0.73	0.71	0.50 (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	6.5[e]
	#B	Improved frame and junctions	0.73	0.71	0.39* (0.50)	70	0.11	0.7	0.025	0.05	0.768	0.93	1.35	14.1
	#C	Improved glazing, 2-pane added	0.46	0.41	0.30* (0.40)	55	0.09	1.5	0.050	0.10	1.460	1.15	1.50	16.0
	#D	Improved glazing, frame and junctions (#B + #C)	0.46	0.41	0.30* (0.40)	55	0.11	0.7	0.025	0.05	0.768	0.75	1.02	16.9
	#E	2-pane glazing with higher *g*-value	1.40	1.10	0.43* (0.60)	78	0.09	1.5	0.050	0.10	1.460	1.85	2.62	11.9

[a] Values representing close to ideal solar-control coating (marked with '*') assume that the *g*-value equals 55% of the light transmittance (LT). Values used for north-oriented glazing with no need for solar control are shown in brackets.
[b] Specific heat loss of frame and junctions (including the connection between roof/walls and window) for a window with standard outer dimensions of 1.23 by 1.48 m.
[c] U'_w includes all heat loss from glazing, frame and junctions, as projected onto the window area, and refers to the window with standard dimensions above.
U'_g includes all heat loss from glazing, frame and junctions, as projected onto the glazed area, and refers to the area-weighted average of the actual window dimensions inserted in the houses. Both coefficients are given for the effective slope.
[d] Total window area inserted in the building.
[e] Only south-oriented roof windows were improved.

Table 3
Properties of glazing, frame and junctions for the reference roof and façade windows (REF) and for the five examples of roof window improvements (#A–E) investigated – Case B.

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients[c]		Total window area[d]
			U_g 00° (W/m² K)	U_g 90° (W/m² K)	g-value[a] (–)	LT (%)	Width (m)	U_f (W/m² K)	Psi g (W/m K)	Psi w (W/m K)	Specific heat loss[b] (W/K)	U'_w (W/m² K)	U'_g (W/m² K)	A_{win} (m²)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.86	31.7
Roof	REF	Best standard practice	1.25	0.90	0.39*	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#A	Higher g-value	1.25	0.90	0.55	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#B	Improved frame and junctions	1.25	0.90	0.39*	70	0.11	0.7	0.025	0.05	0.768	1.29	1.94	9.1
	#C	Improved glazing, 3-pane added	0.50	0.38	0.28*	50	0.09	2.3	0.030	0.10	1.730	1.33	1.81	10.8
	#D	Overall improvement, 3-pane added in the light well	0.50	0.38	0.28*	50	0.09				0.375	0.58	0.79	10.8
	#E	Same as #D, but the added pane is diffuse	0.50	0.38	0.28*	50 diff	0.09				0.375	0.58	0.80	10.1

[a] Values representing close to ideal solar-control coating (marked with '*') assume that the g-value equals 55% of the light transmittance (LT). Values used for north-oriented glazing with no need for solar control are shown in brackets.

[b] Specific heat loss of frame and junctions (including the connection between roof/walls and window) for a window with standard outer dimensions of 1.23 by 1.48 m.

[c] U'_w includes all heat loss from glazing, frame and junctions, as projected onto the window area, and refers to the window with standard dimensions above.
U'_g includes all heat loss from glazing, frame and junctions, as projected onto the glazed area, and refers to the area-weighted average of the actual window dimensions inserted in the houses. Both coefficients are given for the effective slope.

[d] Total window area inserted in the building.

Table 4
Maximum space-heating demand for the houses according to Danish Building Regulations for 2010, 2015 and 2020 (nearly zero-energy), and the *U*-values needed to meet these targets for the reference scenario.

	Case A			Case B		
	2010	2015	2020	2010	2015	2020
Maximum space-heating demand (kWh/m^2)	40.0	22.0	12.0	40.0	22.0	12.0
Space-heating demand of reference (kWh/m^2)	39.9	21.9	12.0	39.7	21.9	12.0
U-value wall (W/m^2 K)	0.31	0.22	0.14	0.25	0.17	0.10
U-value roof (W/m^2 K)	0.31	0.18	0.10	0.22	0.13	0.07
U-value ground floor (W/m^2 K)	0.30	0.18	0.10	0.22	0.13	0.07
Energy saved per cm increased insulation thickness[a] (kWh/m^2 cm)	3.5547	1.1468	0.3463	2.5439	0.8417	0.2522

[a] Extracted from EnergyPlus simulations of the houses with 25 mm more insulation in all constructions.

upper comfort limit provided by Class II of this model (referred to as ‘Adaptive Limit’) for more than 100 h per year. This corresponds well with the recently updated comfort criterion for homes in the Danish Building Code of maximum 100 h above 27 °C [11,23]. Throughout this paper, the number of hours with operative temperatures exceeding 26 °C will also be provided for information, since this was the parameter previously used in Denmark for evaluation of thermal comfort in residential buildings [24].

2.1.3. Evaluation of daylighting

Danish legislation only vaguely defines sufficient daylighting in buildings. For this study, windows were dimensioned based on two criteria for sufficient daylighting, corresponding to those used in previous studies on roof and façade windows at room level [6,7]. With ‘space’ referring to measuring positions evenly distributed over a horizontal plane 0.85 m above floor level, these are:

(1) Illuminance levels of at least 300 lx in 75% of the space for 50% of the daylight hours (Spatial coverage of DA 50% ≥ 75%).
(2) Daylight factors of at least 2.1% in 50% of the space (Median DF ≥ 2.1%).

The first criterion is based on recommendations for Spatial Daylight Autonomies in offices established by IES [25]. This criterion is fully climate-based and the main basis used for designing all spaces in the houses for comparable daylighting. The second criterion refers to an approach presented by Mardaljevic and Christoffersen [26,27] that relates daylight factors to the diffuse daylight access at a specific location. For a position in the room that meets the daylight factor suggested above for the Danish climate, diffuse daylight levels of at least 300 lx should be received in that position for 50% of the daylight hours. This criterion was used together with the fully climate-based criterion to ensure that daylighting in the rooms receiving the most direct sun will meet some minimum standards under overcast conditions. Throughout this paper, the percentage of daylight hours with illuminances exceeding 300 lx in 50% of the space (Median DA), which should preferably be around 60%, will also be provided for information. It was assumed that occupants can use internal screens or curtains to avoid glare if needed.

2.2. Set-up of the windows for daylighting and thermal comfort

In addition to venting through opening of windows, appropriate window design is essential for achieving sufficient daylighting in a space without overheating. Previous studies on the impact of roof and façade windows on energy, daylighting and thermal comfort in nearly zero-energy homes [6,7] have shown that sufficient daylighting can be achieved in solar-exposed rooms without overheating by using well-dimensioned windows with close to ideal solar-control coating (*g*-value as close to half of the light transmittance of the glazing as possible). This was true as long as the rooms had a reasonable layout for daylighting, meaning that it was generally possible to position the windows for good daylight distribution. For example, façade windows should be used only to serve areas closer to the façade than approximately 4–5 m [6], otherwise the overly large glazing areas needed to provide the innermost parts with daylighting would lead to overheating. For rooms with such a reasonable layout for daylighting, the studies showed that, whatever the choice of light transmittance (LT) for the glazing, the use of solar-control coating left some flexibility between the minimum glazing size for daylighting and the maximum glazing size for thermal comfort.

These findings (summarised in Table 5) give reason to believe that houses with any floor plan can be set up for sufficient daylight and thermal comfort, based on information about the glazing area needed for daylighting in just a few typical rooms, by following this approach:

(1) Divide each thermal zone into spaces that can reasonably be served by windows with a certain slope and orientation (referred to as ‘daylit spaces’).
(2) For each daylit space, use the information about daylighting in typical rooms to select the glazing area needed with the given LT, and use common-sense design rules for daylighting to position a number of windows in the space having this glazing area in total.
(3) Use close to ideal solar-control coating on south/east/west-oriented and horizontal glazing, and leave the *g*-values for north-oriented glazing as high as possible to maximise solar gains.

In the present study, this approach was used to set up the two houses for sufficient daylighting and thermal comfort. For the reference scenario, the glazing area needed in each daylit space was first estimated using the glazing-to-floor ratios for minimum daylighting in Table 5. Then daylighting was tested through annual simulations of the hourly illuminance distributions in DAYSIM. Where needed, the size and position of the windows were adjusted using one to two iterations.

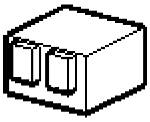
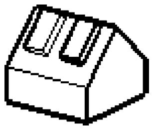
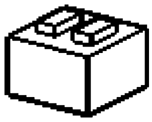
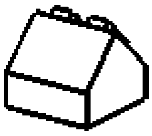
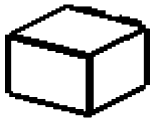
For the scenarios with other light transmittances of the roof window glazing than in the reference scenario (70%), glazing sizes were adjusted in accordance with the change in LT using a scaling factor extracted from Table 5.

2.2.1. Example of window dimensioning for the reference scenario

Tables 6 and 7 show rather detailed information about how the reference scenario was set up for daylighting: the division of the houses into daylit spaces, the glazing area and dimensions inserted in each space, and the final daylight achievements in each thermal zone. The final daylight distributions are also shown in the plan drawings for the two houses in Figs. 1 and 2.

To exemplify the approach, Fig. 2 sketches the division of the kitchen/living room in Case B (Zone 1) into three different daylit spaces, (a)–(c). The front part (a) at a maximum distance of 4.2 m

Table 5
Glazing-to-floor ratios (%) needed in previously studied rooms[a] [6,7] with reasonable layout for daylighting, to achieve daylighting of 300 lx in 75% of the space for 50% of the daylight hours (Spatial coverage of DA 50% ≥ 75%). The ratios needed for a daylight factor of 2.1% in half of the space (Median DF ≥ 2.1%) are shown in brackets. The table also indicates the need for solar-control coating to avoid overheating.

Orientation	South		Horizontal		North
Slope	90°	45°	00°	45°	90°
					
LT 70%	15.6 (17.8)	9.7 (8.5)	10.0 (6.6)	13.2 (8.5)	21.3 (17.8)
LT 60%	17.4 (20.2)	11.0 (9.6)	11.5 (7.5)	15.1 (9.6)	24.5 (20.2)
LT 50%	20.7 (23.7)	12.7 (11.2)	13.2 (8.7)	17.9 (11.2)	29.5 (23.7)
LT 40%	25.0 (30.1)	15.0 (13.6)	16.0 (10.5)	21.4 (13.6)	36.4 (30.1)
LT 30%	34.1 (43.0)	19.2 (17.6)	20.8 (13.2)	27.9 (17.6)	– (43.0)
LT 20%		27.8 (25.4)	31.4 (19.0)	40.2 (25.4)	
LT 10%		45.2 (42.0)	54.5 (38.6)		
Solar-control coating[b]	Close to ideal	Close to ideal	Close to ideal	Not needed	Not needed

[a] These rooms assumed a glazing head-height of 2.4 m for façade windows and thicknesses of 0.45 m for both roof and walls.
[b] Close to ideal solar-control coating means that the *g*-value equals nearly half of the light transmittance (LT).

from the façade was side-lit by south- and west-oriented façade windows, while the central kitchen-part (b) was top-lit by two roof windows positioned to give as even a distribution of daylight as possible. Finally, the corridor (c) was given one central roof window. The latter is not an optimal choice for daylight distribution, but a compromise with practical considerations, since too many small windows would lead to greater heat losses through frame and junctions and more absorption of light in the light well than fewer windows of a reasonable size.

South-, east- and west-oriented façade glazing was dimensioned based on the glazing-to-floor ratios of 17.8% suggested in Table 5 for the diffuse criterion (Median DF ≥ 2.1%), while all other glazing was dimensioned based on the climate-based criterion (Spatial coverage of DA 50% ≥ 75%).

Since differences between the zone floor area (used for determining ventilation rates and internal heat loads) and the area used for evaluation of daylighting may affect the chances of finding a window design that provides sufficient daylighting without overheating, Tables 6 and 7 also include a parameter indicating the daylit fraction of each zone.

2.2.2. *Evaluation of daylight achievements and final glazing ratios for the reference scenario*

The performance indices in Tables 6 and 7 and the daylight distributions in Figs. 1 and 2 generally show well-lit houses where the daylight criteria are met in most zones, while some spaces had more difficult conditions for daylighting than others. The north-oriented bathroom in Case A (Zone 4), for example, was generally well-lit, but too large for the light to be properly distributed with only one window. The same was the case for the storage/activity room in Case B (Zone 6). It should also be noted that the kitchen/living room on the ground floor in Case A (Zone 6) received 300 lx for 50% of the time in almost the entire space. Under overcast conditions, however, this room was slightly too deep to receive sufficient daylighting at the back.

Comparison of the glazing-to-floor ratios finally inserted (Tables 6 and 7) with the ratios suggested for glazing with LT 70% in Table 5 shows that these are very similar for both roof and façade windows in Case B. In this house, the ratios inserted were on average less than 1% greater than the ratios suggested. For the sloped roof windows in Case A, however, the glazing-to-floor ratios inserted were approximately 4–6% more than the ratios suggested. This may partly be due to the difficulties in achieving a coverage of 75% in some of the loft rooms with one-sided sloped ceilings, where the difficult layout for daylighting was typically compensated for by increasing the glazing size of the roof windows rather than the façade windows. Furthermore, the ratios inserted for south/east/west-oriented façade windows in Case A were on average about 2% greater than the ratios suggested, which may be partly due to the lower head-height for façade windows in this house.

2.3. *Insulation for the three different space-heating targets*

Fig. 4 shows for the reference scenario how the insulation thicknesses needed for walls, roof and ground floor to meet the three space-heating targets (see Section 2.1.1) were extracted from simulations of the two houses with various insulation levels, using linear interpolation between the nearest steps. Insulation material with a heat conductivity of 0.037 W/m K was assumed. Table 4 shows the resulting insulation thicknesses and *U*-values for the reference scenario. It should be noted that the insulation levels corresponding to the 2010 and 2015 requirements were included only to show how the findings were affected by the space-heating demand of the reference. With the nearly ideal building components assumed in the present study, these should not be taken as reflecting realistic insulation levels for buildings constructed in accordance with 2010 and 2015 requirements.

2.4. *Evaluation of thermal comfort for the reference scenario*

From the thermal comfort indices shown for the reference scenario in Fig. 5, it can be seen that there are a number of critical zones in each house. One is the kitchen/living room in Case A (Zone 6), where it was difficult to achieve sufficient daylighting during overcast conditions due to the room depth. Another critical room in this house is the southeast-oriented bedroom on the 1st floor (Zone 2), where daylighting was only just met and the only transmission area is the large south-facing roof surface and a small wall facing east. However, for such zones with solar-exposed roof, it can be seen that increased insulation thicknesses in the roof generally improved comfort. In Case B, the most critical room is Zone 6 with transmission only through the roof and ground floor.

With a standard maximum air change rate for venting of 3 h^{-1} [24], these critical zones had between 150 and 170 h with temperatures exceeding 26 °C every year. However, if doubling the venting rate or evaluating the comfort in accordance with the ATC model, none of the zones had more than 100 h per year with excessive

Table 6
Set-up of the reference scenario for daylighting for Case A, showing the division of the house into daylit spaces, the glazing inserted for each space and the resulting daylight achievement in each thermal zone. The light transmittance of all glazing is 70%, and the area-weighted average glazing-to-floor ratio finally inserted in the various types of spaces is shown in brackets underneath the slope and orientation. Performance indices that do not meet the targets are marked with '*'.

Zone with daylit spaces		Zone floor area (m^2)	Floor area of daylit space (m^2)	Inserted glazing-to-floor ratios				Inserted glazing		Daylit fraction of zone (–)	Daylight performance indices		
				S/E/W-90° (20%)	N-90° (22%)	S-45° (14%)	N-45° (19%)	Area (m^2)	Dimension[a], nR/F: $w \times h$ (m)		Spatial coverage of DA 50% (%) (target: ≥75)	Median DA (%) (≥60)	Median DF (%) (≥2.1)
1	*Activity etc. S/N*	*33.9*									*74*,[b]*	*60*	*2.3*
	- Main part		20.0			14.0%		2.80	2R: 1.0 × 1.4	0.83			
	- Stairs		4.4				18.1%	0.80	1R: 0.8 × 1.0	1			
	- Entrance		5.4		22.2%			1.20	1F: 1.0 × 1.2	1			
2	*Bedroom S/E*	*12.8*									*75*	*63*	*2.2*
	- Façade part		4.2	19.0%				0.80	1F: 0.8 × 1.0	0.93			
	- Inner part		7.7			12.4%		0.96	1R: 0.8 × 1.2	0.93			
3	*Bedroom N/E*	*12.8*									*75*	*66*	*3.2*
	- Façade part		4.2	19.0%				0.80	1F: 0.8 × 1.0	0.93			
	- Inner part		7.7				18.1%	1.40	1R: 1.0 × 1.4	0.93			
4	*Bathroom N*	*7.6*	6.8				20.5%	1.40	1R: 1.0 × 1.4	0.90	*67**	*67*	*4.3*
5	*Large bedroom S/N/W*	*23.9*									*75*	*63*	*3.0*
	- Façade part		4.2	19.0%				0.80	1F: 0.8 × 1.0	0.93			
	- Inner part		7.5				18.5%	1.40	1R: 1.0 × 1.4	0.93			
	- Walk-in		6.4			15.7%		1.00	1R: 1.0 × 1.0	0.56			
6	*Kitchen/living S/W*	*52.1*	52.1	20.3%				10.56	3F: 1.0 × 2.0, 1F: 1.4 × 1.2, 2F: 1.2 × 1.2	1	*96*	*63*	*1.9**
7	*Bedroom S/E*	*13.8*	13.8	20.9%				2.88	1F: 1.4 × 1.2, 1F: 1.0 × 1.2	1	*95*	*66*	*2.2*
8	*Utility room N/E*	*12.1*									*83*	*63*	*2.4*
	- Back part		6.4		22.5%			1.44	1F: 1.2 × 1.2	1			
	- Gable part		5.7	21.1%				1.20	1F: 1.0 × 1.2	1			
9	*Bathroom N*	*9.3*	9.3		21.6%			2.00	1F: 2.0 × 1.0	1	*90*	*60*	*2.5*
10	*Bedroom N/W*	*12.0*									*94*	*65*	*2.5*
	- Back part		6.3		23.0%			1.44	1F: 1.2 × 1.2	1			
	- Gable part		5.7	21.1%				1.20	1F: 1.0 × 1.2	1			

[a] Glazing head-height for façade windows was 2.1 m.
[b] Daylight achievements for this zone were affected by the difficult daylight conditions in the entrance. For most of the zone, the spatial coverage was 87%.

Table 7

Set-up of the reference scenario for daylighting for Case B, showing the division of the house into daylit spaces, the glazing inserted for each space and the resulting daylight achievement in each thermal zone. The light transmittance of all glazing is 70%, and the area-weighted average glazing-to-floor ratio finally inserted in the various types of spaces is shown in brackets underneath the slope and orientation. Performance indices that do not meet the targets are marked with '*'.

Zone with daylit spaces		Zone floor area (m^2)	Floor area of daylit space (m^2)	Inserted glazing-to-floor ratios			Inserted glazing		Daylit fraction of zone (–)	Daylight performance indices		
				S/E/W-90° (19%)	N-90° (22%)	00° (11%)	Area (m^2)	Dimension[a], *nR*/*F*: $w \times h$ (m)		Spatial coverage of DA 50% (%) (target: ≥75)	Median DA (%) (≥60)	Median DF (%) (≥2.1)
1	*Kitchen/living S/W*	*76.5*								*87*	*62*	*2.5*
	- Façade part (a)		41.6	17.8%			7.40	3F: 1.0 × 2.0, 1F: 1.0 × 1.4	1			
	- Inner part (b)		24.1			10.6%	2.56	2R: 0.8 × 1.6	1			
	- Corridor (c)		10.8			10.4%	1.12	1R: 0.8 × 1.4	1			
2	*Bedroom (S)/E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 × 1.4	1	*97*	*62*	*2.3*
3	*Bedroom E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 × 1.4	1	*97*	*62*	*2.3*
4	*Bedroom E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 × 1.4	1	*97*	*63*	*2.4*
5	*Bedroom (N)/E*	*11.7*	11.7	19.1%			2.24	1F: 1.6 × 1.4	1	*94*	*62*	*2.2*
6	*Storage/activity (–)*[b]	*10.1*	10.1			11.1%	1.12	1R: 0.8 × 1.4	1	*64**	*55**	*3.3*
7	*Utility room N*	*12.6*	12.6		21.1%		2.66	1F: 1.9 × 1.4	1	*94*	*62*	*2.7*
8	*Large bedroom W*	*21.1*								*70**	*57**	*2.1*
	- Main part		11.7	19.1%			2.24	1F: 1.6 × 1.4	1			
	- Walk-in		5.9			10.9%	0.64	1R: 0.8 × 0.8	0.63			
9	*Bathroom W*	*9.4*								*72**	*56**	*2.7*
	- Façade part		3.5	20.0%			0.70	1F: 0.7 × 1.0	1			
	- Inner part		5.9			10.9%	0.64	1R: 0.8 × 0.8	1			
10	*Bathroom N/W*	*7.0*								*74**	*61*	*2.5*
	- West part		3.5	20.0%			0.70	1F: 0.7 × 1.0	1			
	- North part		3.5		25.6%		0.90	1F: 0.9 × 1.0	1			

[a] Glazing head-height for façade windows was 2.3 m.

[b] No façade, only roof windows.

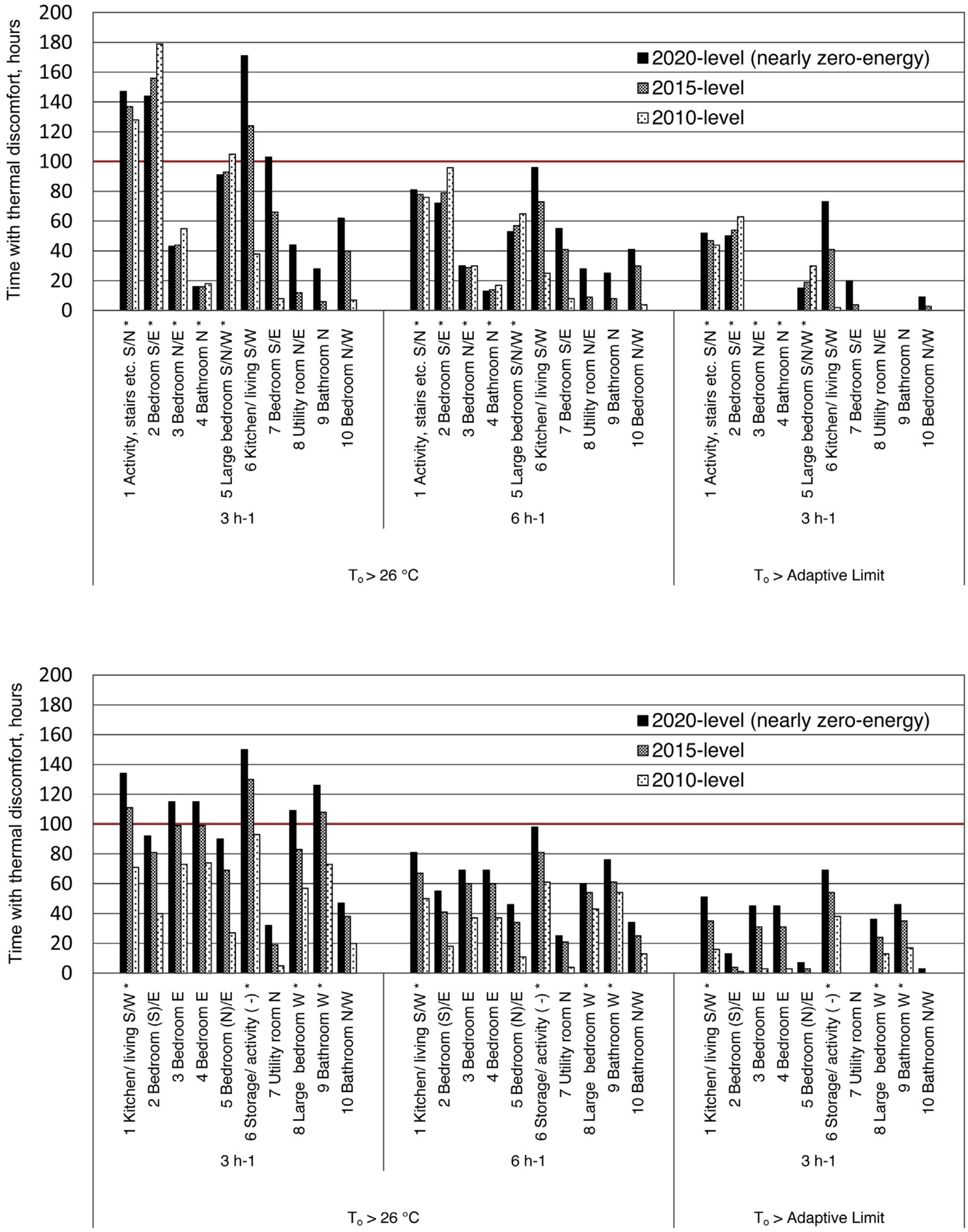


Fig. 5. Time with operative temperatures (T_o) in the various zones exceeding 26 °C and the adaptive thermal comfort limit for the reference scenario. The results are shown for Case A (top) and Case B (bottom) for the three different insulation levels and the maximum air change rates for venting of 3 h^{-1} and 6 h^{-1}. Zones with roof windows are marked with '*'.

temperatures (see Fig. 5). Thus, thermal comfort criteria were met following the approach suggested in Section 2.2.

2.5. The examples of roof window improvements #A–E

A number of realistic options for improving the roof windows (#A–E in Fig. 6 and Tables 2 and 3) were selected for investigation. These range from improvements in the frame and junctions (#B) or the glazed part (#C) alone, to changes that reduced heat losses in all three components at once (#D). #A was included to represent the effect of removing the solar-control coating on all solar exposed glazing. Moreover, an improvement (#E) whereby the *g*-value was increased to more than 0.5 by allowing a higher heat loss coefficient of the glazing (U_g) was included for Case A.

The improvements of the glazed part (#C) were composed on the basis of already existing 2- and 3-pane glazing, to be able to define the changes in the glazing parameters as realistically as possible. Glazing sizes were always adjusted in accordance with the changes in light transmittance to maintain sufficient daylighting, using the following scaling factors extracted from Table 5:

- 1.24, when moving from LT 70% to 55% in Case A.

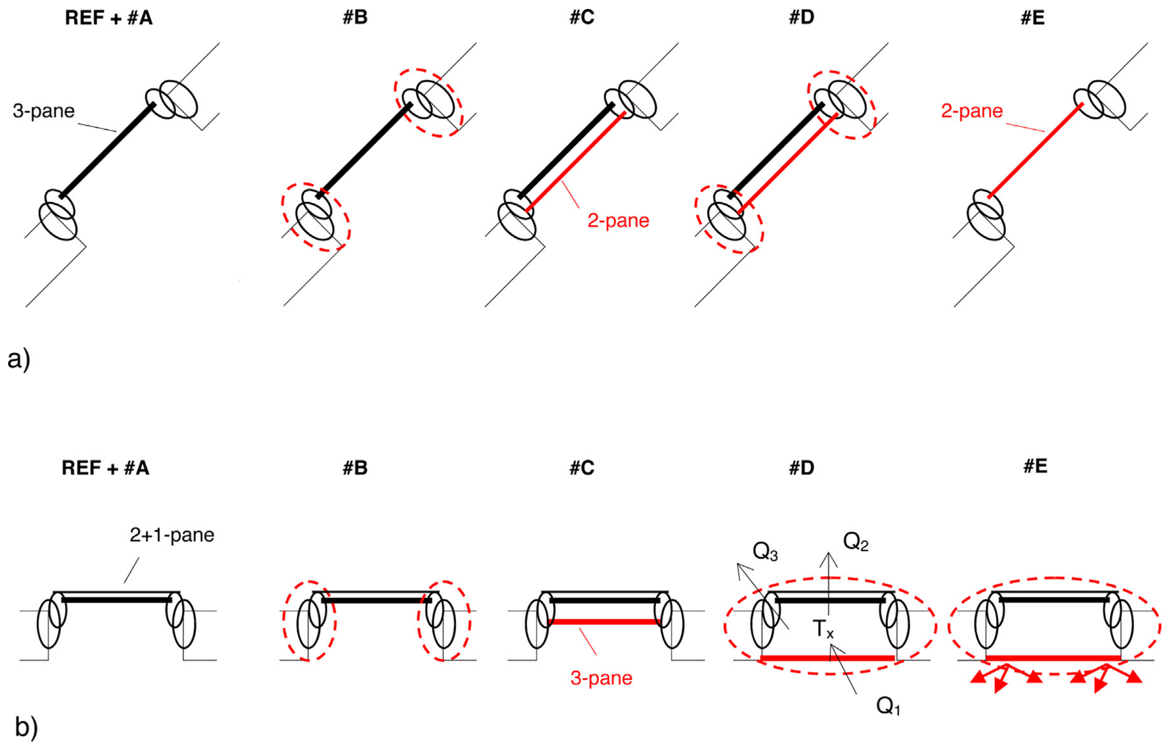


Fig. 6. Sketch of the options for improving the roof windows investigated for Case A (top) and Case B (bottom), indicating the heat balance approach used to estimate the thermal properties of glazing and frame when adding the 3-pane glazing at the bottom of the light well in Case B (#D and E).

- 1.32, when moving from LT 70% to 50% in Case B.
- 0.89, when moving from LT 70% to 78% in Case A.

Frame width was always kept constant when changing the glazing size. This decreased the contribution from frame and junctions per area when increasing the glazing size, which improved the total heat loss coefficients (such as U_g' in Tables 2 and 3).

For the sloped roof windows in Case A, the combined improvement (#D) is similar to an already existing product tested in passive houses, but not yet commonly available. For the horizontal roof windows in Case B, which do not necessarily have to be openable, the combined improvement (#D) was taken further to a solution with a 3-pane glazing added at the bottom of the light well. The heat loss coefficient of this improvement was estimated using the heat balance approach sketched in Fig. 6, which assumes that all heat loss of frame and junctions would pass through the light well.

This option also offered the potential of improving the daylight distribution in the rooms by letting the pane added at the bottom of the light well transmit daylight diffusively (#E). The effect of this diffuse transmittance was found to depend strongly on room size and layout, ranging from no effect in Zone 8, to improvements in daylighting corresponding to that found with 10% higher LT in Zone 1 and 2% higher LT in Zones 6 and 9. This meant that the glazing area of the roof windows in Zones 1, 6 and 9 could be decreased to the area needed with LT 60% and 52% respectively.

2.6. Determining the scope for investment

The scope for investing in improved roof windows was determined based on the insulation costs saved by installing the improved roof windows instead of the current best standard-practice solutions. The average cost I_{ins} per surface area of increasing the insulation thickness in walls, roof or ground floor by 1 cm was estimated to EUR 1.613/(cm m^2) excluding VAT, based on the prices used by the Danish Building Research Institute in a study of cost-optimal energy use in homes [10].

2.6.1. Simplified estimation for small improvements

The scope for investing in a roof window improvement with small impact on the space-heating demand can be estimated with reasonable accuracy by multiplying the energy saved by installing the improvement ΔE_{win} by the cost of saving 1 kWh/m^2 by increasing the insulation for the reference scenario. The insulation costs saved in EUR per m^2 improved roof window A_{win} are then:

$$\text{Saved insulation costs} = \left(\Delta E_{win} \cdot \frac{I_{ins} \cdot A_{ins}}{\Delta E_{ins}}\right) / A_{win} \quad (1)$$

where ΔE_{ins} is the energy saved at building level by increasing the insulation thickness in all constructions by 1 cm (see Table 4) and A_{ins} (411 m^2 for Case A and 573 m^2 for Case B) is the surface area of the constructions after subtraction of roof and façade window area (see Tables 1–3).

2.6.2. Direct calculation based on the insulation not needed

For the specific roof window improvements #A–E, the scope for investment was found directly by comparing the cost of the insulation needed before and after installing the improvements. The insulation costs saved in EUR per m^2 improved roof window were then:

$$\text{Saved insulation costs} = \frac{(V_{ins\ \ ref} - V_{ins\ \ impr}) \cdot I_{ins} \cdot 100}{A_{win}} \quad (2)$$

where $V_{ins\,ref}$ is the volume of the insulation needed in the reference scenario and $V_{ins\,impr}$ is the volume of the insulation needed with the improved roof windows.

The insulation thicknesses needed with improved roof windows were found using the procedure in Section 2.3, and changes in window size were taken into account when calculating the volumes.

2.6.3. Considerations on the differences in lifetime

The lifetime of the roof window is part of the development of a competitive product and may also differ for the various components of the window, so for transparency, the scope for investment presented throughout this paper does not include any corrections for differences in lifetime between window and insulation. Instead the scope for investment is presented directly as the savings in insulation costs defined above, which will then have to cover any necessary replacements of glazing and/or window as a whole within a time frame corresponding to the lifetime of insulation. Assuming that the lifetime of the building envelope is 40–60 years [10], the lifetime of the insulation and the window construction could be fairly similar, whereas sealed glazing units may have to be replaced 1–2 times. The savings in insulation costs will therefore typically have to be divided by two or three to find the competitive price of the improvement per area for the final window product.

2.7. Further modelling assumptions

2.7.1. Daylight simulations in DAYSIM

Daylighting was evaluated based on a sensor point grid with a 0.2 m mask width positioned 0.85 m above floor (or stair) height. The grid covered only useful floor space in the houses with a height-to-ceiling of at least 1 m. For simplicity, all daylight simulations assumed wall and roof thicknesses of 0.45 m and 0.7 m respectively, irrespective of insulation level, and no external obstructions were taken into account. Surface reflectance was 70% for walls and ceilings, 80% for roof window light wells, and 30% for floors.

2.7.2. Thermal simulations in EnergyPlus

The properties of glazing and frames were modelled in EnergyPlus using the simple glazing material method [28]. The houses were modelled using internal dimensions as the transmission areas, and most rooms were modelled as separate zones (see Figs. 1 and 2), neglecting heat and air flows between zones. The basic infiltration rate was assumed to be the same in all zones irrespective of their contact to the outdoor environment (see Table 1), while infiltration rates reflecting the actual heat losses through cold bridges were inserted for each zone individually. Comparison of the EnergyPlus simulations with simulations in the standard-practice software used in Denmark for documenting the energy performance of buildings (BR15) showed very similar results, as long as the individual zones were modelled separately in both programs.

2.7.3. Weather data

Weather data from the Danish Reference Year [29] were used for both types of simulation.

3. Results and discussion

3.1. The effect of changes to the individual glazing parameters

Fig. 7 (columns 1–3) shows the effect of changes to U_g, g-value and LT (glazing size), one at a time, for the two houses, when using the scenarios with the best standard-practice roof windows with and without solar-control coating as the reference (see definition of REF 0.4 and REF 0.5 in Fig. 3). For Case A, either 4.8 m^2 south-oriented glazing (1st row) or 5.0 m^2 north-oriented glazing (2nd row) was changed, and for Case B, 6.1 m^2 horizontal glazing was changed (3rd row).

The effect of changes to U_g presented in this part could also be used to estimate the effect of changes to the thermal performance of the window in general, if the heat loss of frame and junctions is treated as projected onto the glazed part of the window, via the total heat loss coefficient U_g'.

Since an improvement will often consist of reductions or increases in all three parameters at once, the right-hand column in Fig. 7 shows the minimum and maximum U_g/g-ratios for which a set of simultaneous changes in the parameters will lead to energy savings. These include the effect of LT, assuming that LT will change by the same amount or double as much as the g-value ($X = 1$ or 2), and are defined as follows:

- Minimum U_g/g-ratio ($|dg - 0.1 + X \cdot d\text{LT} - 10\%|/|dU_g - 0.1|$) for an improvement in U_g to compensate for the simultaneous decreases in g-value and LT (black curves).
- Maximum U_g/g-ratio ($|dg + 0.1 + X \cdot d\text{LT} + 10\%|/|dU_g + 0.1|$) for an improvement in g-value and LT to compensate for the simultaneous increase in U_g (grey curves).

The lower the minimum U_g/g-ratio and the higher the maximum U_g/g-ratio, the easier it is to find a set of changes that improves the energy consumption of the glazing.

The large dotted curves without markers indicate the relative importance of improvements to U_g and g-value without considering the effect of LT ($dg + 0.1/dU_g - 0.1$).

Comparison of the U_g and g-value alone (1st and 2nd column in Fig. 7) shows that the effect of changes to the g-value decreased more rapidly with space-heating demand than the effect of changes to U_g. For the scenario with solar-control coating in Case B (REF g 0.4), the savings in space heating resulting from increasing the g-value from 0.4 to 0.5 (grey curve, 2nd column) were reduced by 50% when going from the least insulated building to the building consuming nearly zero-energy. In comparison, the savings from decreasing U_g by 0.1 W/m^2 K (black curve, 1st column) were reduced by 17%. As a result, improvements to the g-value went from being 4.1 times to being only 2.5 times as important as improvements to U_g for the horizontal glazing in Case B (see the large dotted line in the right-hand column). For the south-oriented sloped glazing in Case A, the same relationship changed from 5.0 to 3.4 (and from 3.2 to 2.3 for all roof glazing in this house in total).

With the decreasing ability of the houses to utilise solar gains, the effect of LT (glazing size) changed when going from the highest to the lowest space-heating demand as well (3rd column):

- For the roof windows in Case A facing south, increased glazing size changed from being a way of saving energy to having almost no effect on space heating.
- For the horizontal roof windows in Case B and the roof windows in Case A facing north, increased glazing size led to considerably more space heating with all insulation levels.

If we look at the minimum U_g/g-ratios (black curves) needed for an improvement in U_g to compensate for the simultaneous reductions in both LT (increased glazing size) and g-value, these were considerably higher than the ratios found for the U_g and g-value alone. Moreover, they hardly changed at all with insulation level due to the changing effect of window size (LT) and g-value superseding each other. For improvements in the two houses consuming nearly zero-energy, where LT decreased by twice as much as the g-value ($X = 2$), these ratios were:

- Case A: Minimum U_g/g-ratio of 4.3 (for both orientations).
- Case B: Minimum U_g/g-ratio of 7.7.

The effect of changes to the g-value was however not linear. For solar-exposed roof glazing in both houses (Fig. 7, top and bottom rows), the energy savings from increasing the g-value to above 0.5 (grey curves without fill-in) were 25–30% lower than if the g-value was increased from 0.4 to 0.5 (grey curves with fill-in). This is in line

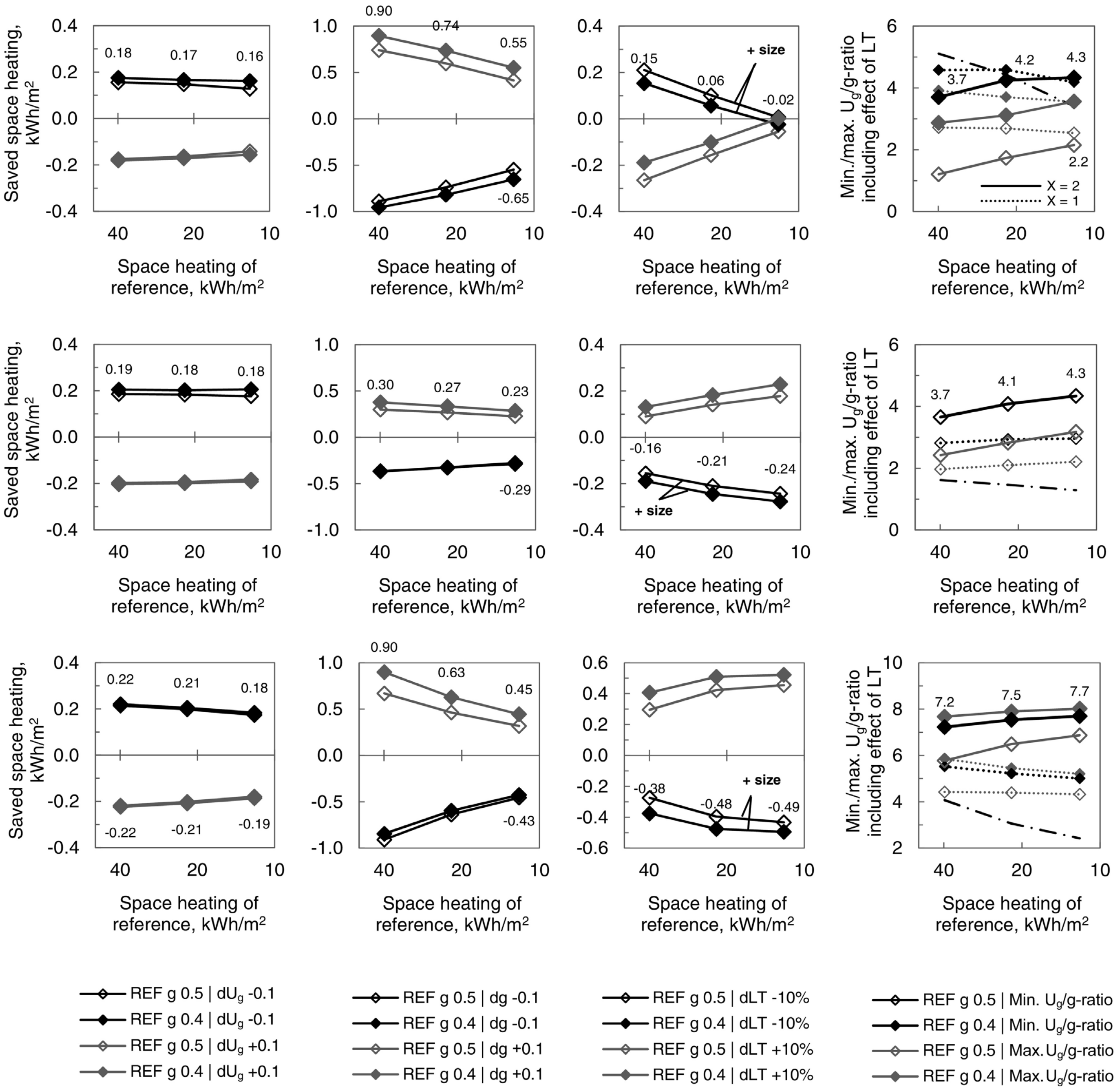


Fig. 7. Effect of changes to U_g, g-value (g) and LT (glazing size) for south- and north-oriented roof window glazing in Case A (1st and 2nd row), and for the horizontal roof window glazing in Case B (3rd row). The minimum U_g/g-ratio ($|dg-0.1+X \cdot dLT - 10\%|/|dU_g - 0.1|$) and the maximum U_g/g-ratio ($|dg+0.1+X \cdot dLT+10\%|/|dU_g+0.1|$) for a set of simultaneous changes in the parameters to save energy are shown in the right-hand column. These include the effect of LT, assuming that LT changes by the same amount or double as much as the g-value ($X=1$ or 2). The larger dotted line shows the relative importance of improvements to U_g and g-value, excluding the effect of LT ($dg+0.1/U_g-0.1$). This line and the data labels refer to REF g 0.4 for horizontal and south-oriented glazing and to REF g 0.5 for north-oriented glazing.

with previous studies [3–7], which found that the effect of increasing the g-value diminished after certain values. As a consequence, the energy savings from increasing the g-value to above 0.5 could compensate for only smaller increases in U_g, which lead to the following maximum U_g/g-ratios for such improvements (grey curves without fill-in):

- Case A: Maximum U_g/g-ratio of 2.2 (south) and 3.2 (north).
- Case B: Maximum U_g/g-ratio of 6.9.

In comparison with the minimum U_g/g-ratios identified above, these ratios are rather small.

The lower utilisation of solar gains and larger consequences of increased glazing size found for Case B than for Cases A may be due to the less-insulated window used as a reference in this house and the larger heat losses for horizontal roof windows than for sloped roof windows. Moreover, zones with roof windows in Case B consumed approximately 11 kWh/m^2, which is considerably less than the space heating consumed by zones with roof windows in Case A (see Tables 8 and 9).

Table 8
Space-heating demand distributed over zones for the reference scenario with nearly zero-energy consumption for Case A. Zones with roof windows are marked with '*'.

Zone		Space-heating demand (kWh/m^2)	Gross floor area[a] (m^2)
1	Activity, stairs, etc. S/N*	11.1	35.2 (0.76)
2	Bedroom S/E*	12.9	14.0 (1.00)
3	Bedroom N/E*	22.2	14.0
4	Bathroom N*	38.3	7.6
5	Large bedroom S/N/W*	17.3	26.2 (0.43)
6	Kitchen/living room S/W	2.7	58.7
7	Bedroom S/E	8.8	17.0
8	Utility room N/E	16.4	15.1
9	Bathroom N	12.0	10.6
10	Bedroom N/W	16.7	15.0
Zones with roof windows		16.8[b]	96.9
Other zones		8.0	116.3
Total		12.0	213.2

[a] Fraction of roof window area in the zone facing south is given in brackets.
[b] Of this, zones with south-oriented roof windows consumed around 13 kWh/m^2 and zones with north-oriented roof windows around 21 kWh/m^2.

Table 9
Space-heating demand distributed over zones for the reference scenario with nearly zero-energy consumption for Case B. Zones with roof windows are marked with '*'.

Zone		Space-heating demand (kWh/m^2)	Gross floor area (m^2)
1	Kitchen/living room S/W*	8.5	83.0
2	Bedroom (S)/E	14.5	17.2
3	Bedroom E	8.6	15.5
4	Bedroom E	8.6	15.5
5	Bedroom (N)/E	16.7	14.6
6	Storage/activity (–)*	16.3	10.1
7	Utility room N	14.4	14.3
8	Large bedroom W*	12.4	23.2
9	Bathroom W*	19.1	10.3
10	Bathroom N/W	24.6	9.5
Zones with roof windows		10.7	126.6
Other zones		13.9	86.5
Total		12.0	213.2

3.2. The effect of the examples of roof window improvements #A–E

Fig. 8 (left-hand side) shows the energy savings at building level from replacing the best standard-practice roof windows in the reference scenario with the improved roof windows #A–E. The scope for investing in the improvements per area of improved roof window (as defined in Section 2.6.2) is shown to the right. The same figure also shows in brackets average changes to insulation thicknesses and changes to thermal comfort in the most critical zones, after the houses have been insulated for the same energy consumption as before. Fig. 9 shows thermal comfort for all relevant zones.

3.2.1. Removed solar-control coating (#A)

Removing the solar-control coating on solar-exposed glazing (#A), corresponds to the maximum change in g-value that can typically be achieved without affecting the U_g or LT of the glazing. This improvement led to savings in space-heating demand of 0.6 kWh/m^2 in both houses, which is slightly more than the savings achieved for the best of the thermal glazing improvements considered in this study. However, while all the other improvements provided similar thermal comfort as for the reference scenario, this improvement considerably increased the time with excessive temperatures (Figs. 8 and 9). The insulation costs of approximately EUR 200 saved by removing the solar-control coating would therefore have to cover the installation and maintenance of dynamic solar shading devices or other supplementary means to avoid overheating.

3.2.2. Thermal improvements to the glazing (#C)

The thermal improvement in the glazing in Case A (#C) turned out almost neutral. An estimate based on Fig. 7 (see Section 3.1) would reveal that the minimum U_g/g-ratio for such an improvement to save energy (when $X = 1.5$) is: $(0.65 + 0.29 + 1.5 \cdot 0.02 + 1.5 \cdot 0.24)/(0.16 + 0.18) = 3.9$, which equals the U_g/g-ratio of 3.9 for the improvement (see changes in g-value and U'_g in Table 2). The considerably better improvement for Case B (U_g/g-ratio of 8.7), on the other hand, led to savings in space-heating demand of 0.5 kWh/m^2, which is reasonable with the minimum U_g/g-ratio of 7.7 for this improvement found in Section 3.1.

The improved glazing in Case B led to savings in insulation costs of approximately EUR 170 per area of improved roof window. Assuming two replacements of sealed glazing units throughout the lifetime for insulation, the improved window may cost EUR 50–60 more per m^2 than the windows that are standard practice today. A similar scope for investment could have been achieved by using this improvement in Case A, where the energy saving potential would be approximately the double, while the costs of saving energy by means of insulation would be almost the half (see Section 3.4).

3.2.3. Glazing with higher transmittances? (#E – Case A)

If we look at the 2-pane glazing in Case A (#E), the increase in g-value of this improvement could not compensate for the 8 and 19 times larger increase in U_g, and it considerably increased space heating. According to Fig. 7 (see Section 3.1), the U_g/g-ratio for this type of improvement to save energy should have been at most 1–2 or 4, which could not have been achieved even if the solar-control coating on south-oriented glazing had been removed.

3.2.4. Improved frame and junctions (#B)

The largest energy savings were achieved when reducing heat losses through frames and junctions. The improvement of frames and junctions alone (#B), which corresponded to changes in U'_g for the inserted glazing of 0.52 $W/m^2\,K$ for Case A and 0.83 $W/m^2\,K$ for Case B (see Tables 2 and 3), led to energy savings of 1.7–1.8 kWh/m^2 in the two houses. This reduced insulation costs per area of improved roof window by around EUR 200 in Case A and EUR 600 in Case B, which would probably have to cover at most 1 replacement if sealed glazing units can be replaced separately.

3.2.5. Combined improvements (#D)

The combined improvement in Case A (#D) shows the effect of improving the frame and junctions (#B) and the glazing (#C) at the same time. From Fig. 8 it can be seen that this resulted in slightly more energy savings than when improving the frame and junctions alone (#B), even though the improvement in the glazing itself (#C) was found to have neutral or slightly negative effect on space heating. This means that the improvement in the glazing had a positive effect on space heating when combined with the improvement in frame and junctions, due to the way the consequences of increased glazing size decreases with improved thermal properties (see Section 3.3). The scope for investment (EUR 200) per area of improved roof window, however, did nearly not change because the savings were distributed onto a larger window area (see Table 2).

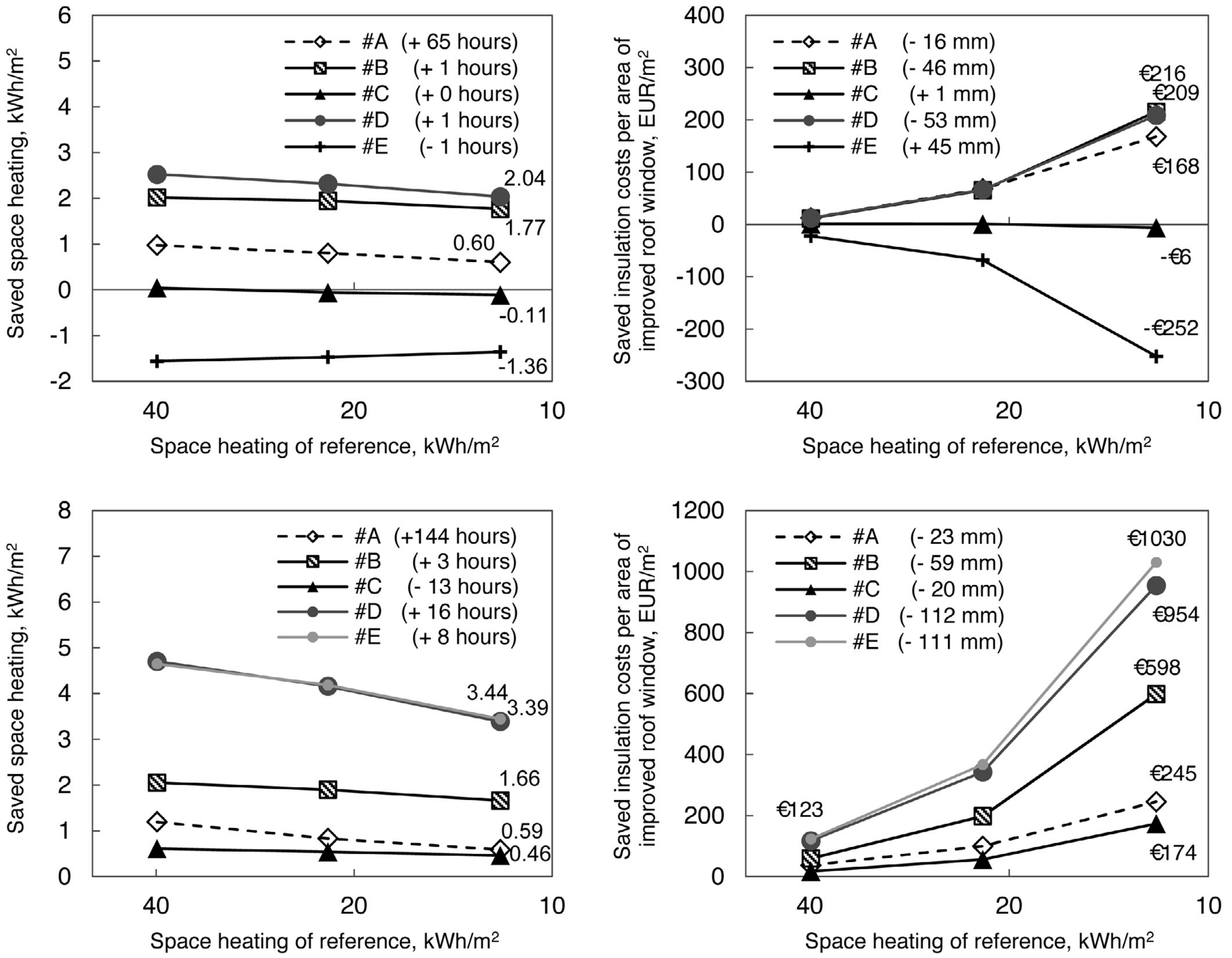


Fig. 8. On the left: Savings in building space-heating demand from replacing the roof windows in the reference scenario with the improved roof windows #A–E for Case A (top) and Case B (bottom). Changes in the number of hours with operative temperatures exceeding the adaptive thermal comfort limit are shown in brackets for the most critical zones (Zones 1 and 6). On the right: The insulation costs saved per area of improved roof window, with the average reduction in insulation thicknesses due to the improvements indicated in brackets.

The combined improvement in Case B (#D) shows the effect of adding a 3-pane glazing at the bottom of the light well, which reduced heat losses through frames and junctions to almost one fifth of those found for the reference window (see the specific heat loss in Table 3). This reduced space-heating demand by 3.4 kWh/m^2, which is twice the energy saved by improving the frame alone (#B), even though the frame construction itself was not changed. On average, this relatively simple improvement would save the building owner more than 100 mm insulation in all constructions and reduce the insulation costs by EUR 950 per area of improved window. If this amount has to cover at most two replacements, the improved roof window could cost up to at least EUR 310–320 more per m^2 than the windows that are best standard practice today and still compete with the investment in 100 mm more insulation.

3.2.6. Glazing with diffuse transmittance (#E – Case B)

If replacing the glazing added at the bottom of the light well in Case B with a 3-pane glazing that transmits daylighting diffusively (#E), slightly less glazing area was needed for sufficient daylighting in Zones 1, 6 and 9. This led to slightly improved thermal comfort (see Figs. 8 and 9) and a scope for investment of EUR 80 more per m^2 improved window than for #D. This exemplifies a permanent approach for improving thermal comfort beyond what can be achieved with solar-control coating.

3.3. Derived effects of installing improved roof windows

Fig. 10 (left-hand side) shows the effect of increasing the glazing sizes to more than needed for sufficient daylighting for the reference window and for the examples of improved windows #A–E. Before increasing the glazing size, the scenarios with improved roof windows were insulated to have the same energy consumption as the reference scenario. The results show that space-heating demand increased less when increasing the glazing size for the improved roof windows than for the reference window. This means that improved roof windows would make it cheaper for building owners to use larger windows in combination with dynamic solar shading or other means to avoid overheating. Furthermore, it means that improvements in the glazed part (that involve reduced LT) will perform better the larger the overall improvement. Fig. 7 would therefore tend to underestimate the energy saving potential of thermal improvements in glazing, frame and junctions combined (such as #D).

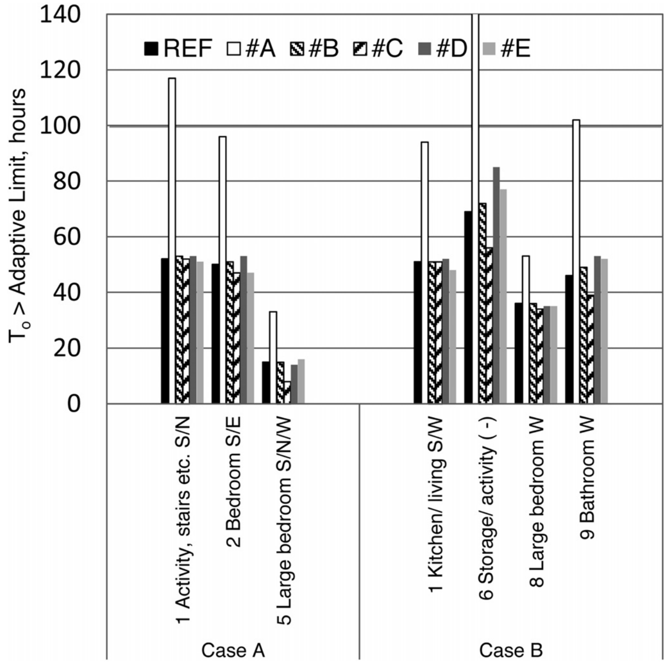


Fig. 9. Hours with operative temperatures exceeding the adaptive thermal comfort limit in zones with solar-exposed roof windows for the reference scenario (REF) and for the scenarios with improved roof windows (#A–E). All scenarios are insulated to comply with the nearly zero-energy target for space heating and the venting rate is $3\,h^{-1}$.

3.4. Sensitivity of the scope for investment

Fig. 10 (right-hand side) shows the costs at building level of saving 1 kWh/m^2 by increasing the insulation thicknesses for the reference scenario and for the scenarios with improved windows #A–E, as presented in Section 3.3. These costs are also shown for a scenario without solar-control coating on the façade windows and for a scenario with less optimal façade windows.

3.4.1. Sensitivity to changes in assumptions

From Fig. 10 it can be seen that removing the solar-control coating on all roof or façade glazing would have made the costs of saving energy by means of insulation for the houses only slightly lower than for the reference scenario. Such changes to the reference scenario would therefore not have affected the scope for investment significantly. If using less optimal façade windows, on the other hand, the costs of saving energy were more than doubled. This illustrates how rather small deviations from the optimal building components assumed could easily increase the scope for investment significantly, which indicates that the savings in insulation costs identified throughout this paper may be considered rather conservative estimates of the scope for investment.

3.4.2. Sensitivity related to application

For minor improvements, such as #A and #C, it can be seen that the costs of saving 1 kWh/m^2 by increasing the insulation is only slightly lower than for the reference scenario. The scope for investing in such improvements could therefore with reasonable accuracy be estimated by multiplying the energy saving potential

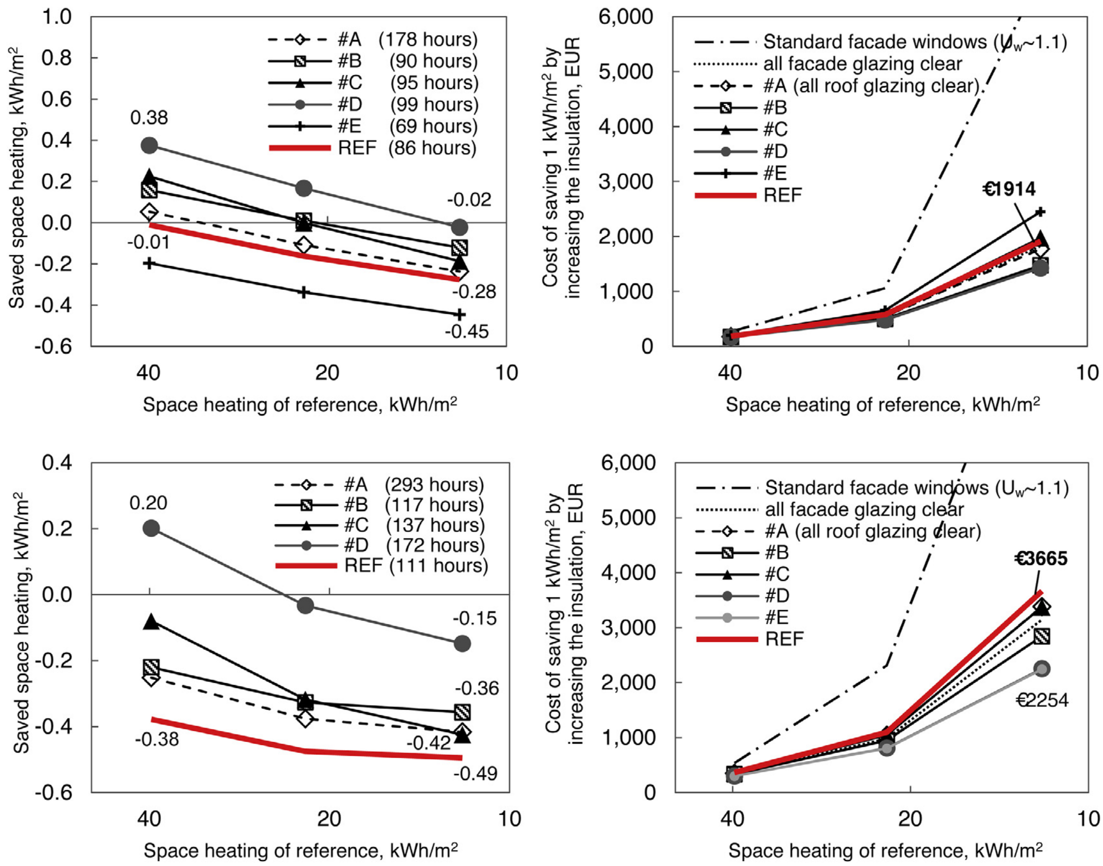


Fig. 10. On the left: The effect on space-heating demand of increasing the window sizes corresponding to LT-10%. On the right: The cost of saving 1 kWh/m^2 by means of insulation. Case A (top) and Case B (bottom). The results are shown for the reference scenario and for scenarios with the improved roof windows. The number of hours with operative temperatures exceeding the adaptive thermal comfort limit after increasing the glazing area is shown in brackets for a venting rate of $3\,h^{-1}$.

of the improvements with the costs of saving 1 kWh/m^2 by means of insulation, as suggested in Section 2.6.1.

For larger improvements, however, such estimations should be used with care. For example, if we multiply the energy savings for improvement #D in Case B by the EUR 3665 needed for the reference scenario to save 1 kWh/m^2 by increasing the insulation, the savings in insulation costs would be estimated to (3665 · 3.39)/10.8 = EUR 1150 per m^2 improved roof window, which is EUR 200 more than found directly through simulation. Similarly, if using the EUR 2254 needed to save 1 kWh/m^2 by means of insulation for the scenario with the improved window (#D), the savings in insulation costs would be underestimated by approximately EUR 250.

4. Conclusions

From the part showing the effect of changes to the heat loss coefficient (U_g), the solar heat gain coefficient (g-value) and the light transmittance (LT) of the glazing, one at a time, we found that the utilisation of solar gains decreased when lowering the space-heating demand of the houses, while the consequences of reducing LT (increasing glazing size) increased. Due to these two tendencies superseding each other, the minimum U_g/g ratios needed for an improvement in U_g to compensate for the simultaneous reductions in both g-value and LT, hardly changed with space heating.

For the two houses consuming nearly zero-energy, a thermal improvement of the glazing led to energy savings if:

- U_g decreased by 4.3 times as much as the g-value in Case A.
- U_g decreased by 7.7 times as much as the g-value in Case B.

These relationships assume that LT will as a maximum decrease by twice as much as the g-value.

Increasing the g-value to above 0.5 (by allowing a higher U_g), could at most compensate for 2–3 and 7 times larger increases in U_g for Case A and B respectively.

From the specific roof window improvements investigated in the second part, we found the following examples of reduced insulation costs in the houses per m^2 improved roof window:

- EUR 170 in Case B for thermal improvements in the glazing (#C). The energy saving at building level was 0.5 kWh/m^2. A similar scope for investment would be expected in Case A.
- EUR 200 in Case A and EUR 600 in Case B for improvements in frame and junctions (#B). The energy savings at building level were 1.7–1.8 kWh/m^2 for the two houses.
- EUR 950 in Case B for a simple combined improvement (#D), where the addition of a 3-pane glazing at the bottom of the light well extensively reduced heat losses through glazing, frame and junctions, all at once. The energy saving at building level was 3.5 kWh/m^2.

The final scope for investment due to the savings above will depend on the lifetime of the products. The windows as a whole may, for example, have to be replaced once and the glazing components twice throughout a period corresponding to the lifetime of insulation (40–60 years). In comparison with the roof window products that are best standard practice today, users would then be able to pay:

- EUR 50–60 more per m^2 window with improved glazing (#C).
- EUR 100–300 more per m^2 window with improved frame and junctions (#B).
- At least EUR 320 more per m^2 window with the 3-pane glazing added at the bottom of the light well (#D).

5. Outlook

These findings show a large potential for improvements in frame and junctions, that we strongly recommend roof window manufacturers to consider. At the same time, results in this study showed that increased glazing size would increase space-heating demand less the better the overall energy performance of an improvement. An improvement in the glazed part would therefore typically perform better in combination with improvements in frame and junctions than alone. Furthermore, it should be noted that the examples of improvements in glazing, frame and junctions presented in this study are based on well-known existing technology, so it is likely that experts will come up with much better options when looking into the possibilities in more detail.

The reduced insulation costs identified throughout this paper show an increasing potential for making improved roof windows available at prices that are less than the prices that would currently be paid to meet near future energy requirements by means of insulation. For every 1 kWh/m^2 saved at building level by improving the roof windows, the insulation costs in the houses were reduced by EUR 1914 in Case A and EUR 3665 in Case B, and these amounts were most likely on the conservative side, due to the optimal building components generally assumed in the houses.

Finally, this study showed how the thermal improvements in glazing, frame and junctions investigated supported an approach where daylighting and thermal comfort criteria were met without the use of more advanced means than well-dimensioned windows for daylighting and solar-control coating on south/east/west-oriented and horizontal glazing. If such competitive roof window products can be made available, this would make it cheaper for users to construct nearly zero-energy homes, and these homes could be designed for sufficient daylighting and thermal comfort throughout in a fairly easy way as well.

Acknowledgements

The authors would like to thank VELUX A/S for their financial support for this research.

References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union, 18/06/2010, Strasbourg, France, 2010.
[2] M.N. Inanici, F.N. Demirbilek, Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey, Build. Environ. 35 (2000) 41–52.
[3] M.-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energy Build. 38 (2006) 181–188.
[4] L. Vanhoutteghem, S. Svendsen, Modern insulation requirements change the rules of architectural design in low-energy homes, Renew. Energy 72 (2014) 301–310.
[5] G.C.J. Skarning, S. Svendsen, C.A. Hviid, Investigation and description of European buildings that may be representative for "nearly zero" energy single family houses in 2020, in: Proceedings of the CISBAT Conference, Lausanne, 4–6 September, 2013, pp. 247–252.
[6] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energy Build. 102 (2015) 149–156.
[7] G.C.J. Skarning, C.A. Hviid, S. Svendsen, Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe, Energy Build. 116 (2016) 602–613.
[8] A. Meier, What is the cost to you of conserved energy? Harvard Bus. Rev. 61 (1) (1983) 36–37.
[9] A. Meier, The cost of conserved energy as an investment statistic, Heat. Pip. Air Cond. 55 (9) (1983) 73–77.
[10] S.O. Aggerholm, Cost-optimal Levels of Minimum Energy Performance Requirements in the Danish Building Regulations, Danish Building Research Institute, Aalborg University, 2013.
[11] Danish Transport and Construction Agency, Building Regulations 2015 Ver. 01.07.2016, 2016, http://bygningsreglementet.dk/br15_01/0/42 (accessed 20.10.16, in Danish).

[12] S. Jaber, S. Ajib, Thermal and economic windows design for different climate zones, Energy Build. 43 (2011) 3208–3215.
[13] H. Karabay, M. Arici, Multiple pane window applications in various climatic regions of Turkey, Energy Build. 45 (2012) 67–71.
[14] S. Hansen, L. Vanhoutteghem, A method for economic optimization of energy performance and indoor environment in the design of sustainable buildings, in: Proceedings of the 5th International Building Physics Conference, IBPC2012, Kyoto, Japan, 28–31 May, 2012, pp. 741–747.
[15] P. Foldbjerg, T. Asmussen, Using ventilative cooling and solar shading to achieve good thermal environment in a Danish Active House, REHVA Eur. HVAC J. 50 (3) (2013) 36–42.
[16] J. Du, B. Hellström, M.-C. Dubois, Daylighting Utilization in the Window Energy Balance Metric: Development of a Holistic Method for Early Design Decisions, Lund University, 2014.
[17] J. Du, Window systems and energy performance in one-family houses: size and shading effects, in: Proceedings of the Building Simulation and Optimization Conference, London, 23–24 June, 2014.
[18] US Department of Energy, EnergyPlus Energy Simulation Software, http://apps1.eere.energy.gov/buildings/energyplus/ (accessed 15.07.15).
[19] Y. Zhang, I. Korolija, Performing complex parametric simulations with jEPlus, in: SET2010 – 9th International Conference on Sustainable Energy Technologies, 24–27 August, Shanghai, China, 2010.
[20] Y. Zhang, 'Parallel' EnergyPlus and the development of a parametric analysis tool, in: IBPSA BS2009, 27–30 July, Glasgow, UK, 2009, pp. 1382–1388.
[21] DAYSIM, Advanced Daylight Simulation Software, http://daysim.ning.com/ (accessed 15.07.15).
[22] European Standard EN 15251. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, CEN, 2007.
[23] S. Petersen, Daylight conditions and thermal indoor climate in low-energy homes – the consequence of Danish building code, in: Proceedings of 7th Passivhus Norden, Sustainable Cities and Buildings, Copenhagen, 20–21 August, 2015.
[24] S.O. Aggerholm, K.E. Grau, SBi-anvisning 213: Bygningers energibehov – Beregnings-vejledning, 3rd edition, Danish Building Research Institute, Aalborg University, 2014 (in Danish).
[25] IESNA, LM-83-12, Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York, NY, USA, IESNA Lighting Measurement, 2012.
[26] J. Mardaljevic, J. Christoffersen, A roadmap for upgrading national/EU standards for daylight in buildings, in: Proceedings of the CIE Centenary Conference, Paris, 15–16 April, 2013, pp. 178–187.
[27] J. Mardaljevic, J. Christoffersen, 'Climate connectivity' in the daylight factor basis of building standards, Build. Environ. 113 (2017) 200–209.
[28] D. Arasteh, C. Kohler, B. Griffith, Modeling Windows in Energy Plus with Simple Performance Indices, Report LBNL-2804E, Lawrence Berkeley National Laboratory, 2009, October.
[29] J.M. Jensen, H. Lund, Design Reference Year, DRY – et nyt dansk referenceår, Technical Report lfv-281, Technical University of Denmark, 1995 (in Danish).

Roof windows are a particularly efficient source to natural daylighting. This thesis examines the possibilities of developing roof windows with an overall improved performance for use in nearly zero-energy houses. It identifies options for improvement that would make it easier and more cost-effective to design and construct nearly zero-energy houses with sufficient daylighting and thermal comfort in all parts, and sketches the increased flexibility in design that would be achieved with improved frame constructions and heat loss coefficients of the glazing lower than current standard levels.

DTU Civil Engineering
Technical University of Denmark

Brovej, Bygning 118
2800 Kongens Lyngby

www.byg.dtu.dk

ISBN 9788778774637
ISSN 1601-2917