Architectural window design and energy efficiency:
impacts on heating, cooling and lighting needs in Finnish climates

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Abstract

The building sector constitutes a significant share of global energy consumption and CO_2 emissions. Despite improving technology and materials, the foundation of successful energy design lies in architectural design decisions. Windows are one architectural design issue that is a key factor in both energy efficiency and functionality. This research utilized dynamic building simulations to study the direct and combined energy impacts of window related architectural design through the following main variables' effect on heating, cooling, and lighting need: window area, proportions, horizontal position, external shading, glazing properties, and adjacent room proportions. Four solar orientations and three climatically different Finnish locations were included as context variables.

Window energy efficiency in the studied cases was found to be primarily about controlling solar heat gain. Geographic location changed not only energy consumption directly, but also the individual variables' impact on it and each other. The results indicate that cooling can be a significant factor even in cold climates, and that energy efficiency should always be evaluated using local weather data as well as sufficient design detail. Most properties affected each other significantly, highlighting a need for a comprehensive approach in both research and design practice and allowing evaluating previous studies comprising fewer variables.

Keywords

Energy performance; Window design; Architectural design; Multivariable simulation; Solar energy

Highlights

Window energy efficiency in the study mainly depended on controlling solar heat gain.

Significant cooling need can exist even in heating dominated climates.

Energy efficiency does not require minimizing window area even in cold climates.

Reliably studying one property requires including a number of related properties.

Declarations of interest

none

1. Introduction

The building sector currently comprises roughly 30% of global delivered energy consumption [1]. For the European Union, the respective figure is 40%, with a correspondingly high share of 36% for CO_2 emissions [2]. In Europe, the Energy Performance of Buildings Directive (EPBD) states that from the year 2020, all new buildings must fulfill the definition of nearly Zero Energy Building (nZEB)—the specifics of the definition are left to each member state, but nevertheless require improvements to current practice [3].

A building's energy efficiency related properties can be broadly divided into active and passive ones [4]. Active ones are for the most part building services related, while passive properties cover structural and other architectural design. Despite improving technology in active technical solutions, as well as structural materials, architectural design, such as building size, form and fenestration, is still significant in laying the baseline for the building's performance (e.g. [5–8]. Directive 2018/844/EU, amending the EPBD and Directive 2012/27/EU, also notes the importance of utilizing passive architectural means for reducing heating, cooling and lighting energy consumption [9]. Doing so can of course significantly affect architectural design. Therefore, it is important for designers to be aware which of their decisions actually affect the building's energy use noticeably and how, as well as how they affect the impact of each other.

One design aspect that links energy efficiency and architectural expression strongly together is window design. From an energy performance perspective, windows have been identified as one of the key elements of building design, often even as the most important one [8,10–14]. Among the reasons for this is that they are always weak from a heat transmittance point of view compared to contemporary wall, floor and roof structures—reference U-values for windows tend to be multiple times higher than for the above (e.g. [15–17]). Estimates have attributed up to half of annual heating energy use in residential buildings to heat losses through windows [12,13,18]. On the other hand, however, windows can also let significant amounts of heat and sunlight inside the building envelope, which can affect heating, cooling and lighting needs as well as thermal [19,20] and visual comfort [21,22]. Relatedly, for architectural expression their significance stems mainly from for example the following aspects: providing natural light, allowing views inside to outside and vice versa, and affecting building appearance (e.g. [10,21]). Following from the above, in the context of energy efficiency, this study focused specifically on architectural window design, i.e. on window related design decisions which directly affect the architectural expression of a building.

Continuing from the energy use of the building sector in general, it has been shown that at least in Europe housing constitutes approximately a quarter of total annual delivered energy consumption [23] In addition to regular housing, the amount of long-term residential care has been increasing for many decades in most of Europe, for the growing number of elderly in particular (usually people at least 65 years of age, a fifth of the European population and rising [24]). This increases the effect of not only housing for the elderly in general but also housing under the service sector [25], not included in the figure above. Due to the residents' frailty, good window design is even more important in these cases than in regular housing: the residents are often very sensitive to changes in temperature and spend most of their time indoors, significantly increasing the impact of both maintaining stable interior conditions and providing sufficient natural light as well as visual connection to the outside [26].

This research studied the energy efficiency effects of window design decisions in apartments, using elderly housing as the specific case, with a focus on architectural design. As elderly housing consists more and more of actual apartment type solutions instead of the traditional hospital-like nursing homes [27], the results are also highly applicable to regular apartments. A set of design variables was chosen (sections 1.1 and 1.2) and all the various combinations simulated (section 2), based on which observations are presented on the design decisions' impact on energy efficiency and therefore advisable design practice (sections 3 and 4). The direct context of the study is Finland, which using the Köppen climate classification is mainly subarctic (Dfc) [28] (see details for studied locations under 2.3.7. Climate). Similar conditions can be found in for example most of the other Nordic countries as well as large parts of Russia and Canada. The climate presents a challenging environment for energy efficient design with high heating need during winter while still having a risk of overheating in summer. The relatively long and dark winters also pose the challenge of maximizing natural light while still managing heat losses—and gains in the summer. In future the changing climate as well as the nZEB requirements can be expected to increase the importance of managing overheating.

1.1. Existing research

On the whole, energy efficient window design has been researched extensively with varying, typically fairly narrow focuses, the context appearing to be mostly housing or offices. A sample of studies published after the year 2000 is summarized in table 1, to illustrate the properties examined in previous research and thus the framework for this study. The sample includes studies using either residential or office buildings, noted in table with R/O, or U when unspecified. There appears to be no connection between building type and included properties, and interpreting the results of any study requires considering for example the set interior conditions and studied zone regardless of building type. Thus, not restricting the sample to only residential buildings serves to provide a more comprehensive picture of existing work. Included are also a variety of locations and climates—while these have a fundamental effect on the specific impact of many design properties, the selection of possible design properties itself is not affected. In accordance to the topic of this study the recorded properties in table 1 have been grouped into direct window properties, adjustable in the context of a single window, and other properties closely related to window design. For direct window properties, it has been noted whether all possible combinations of the variables were examined (C), or whether the variables were studied in isolation (I). For other related properties, it is simply marked if the variable was included at all (X). The listed properties themselves were selected based on their occurrence in the sample.

Table 1. Properties studied in existing research on energy efficient window design.

Window properties																																									
Area	C	C	C	C	C	C	C		C	C	C	C		C	C	C	C	C	C	I	I	I	I	I	I	I		I	I							I	I	I	I	I	
Glazing	C		C	C	C	C	C	C	C	C	C	C	C			C			C	I	I		I	I	I	I				I	I	I	I		I						I
Position															C		C										I														
Shape		C												C													I														
Shading	C							C					C					C		I		I												I							
Related properties																																									
Facade orientation		X	X	X	X	X	X			X	X	X	X	X	X					X	X	X	X						X	X	X		X	X		X	X	X	X		
Climate		X	X	X	X			X	X							X				X	X	X		X				X		X		X			X						
Room shape		X	X			X																						X	X												
Building type	O	O	O	R	R	R	O	R	O	O	R	O	R	R	R	R	O	O	O	R	O	R	R	R	O	O	R	O	R	U	R	R	U	R	R	R	O	O	O	R	R
Studied country	USA	USA	USA	DEU, JOR	KOR	DNK	KWT	USA	ITA	CAN	JOR	LTU	IRN	PSE	CAN	DNK, ITA	NLD	CAN	SWE	ITA	CHN + 4^{a}	SVN	SWE	GRC	SWE	GBR	IRN	BRA, GBR	BRA, GBR	CHE + 7^{b}	SWE	SWE	SWE	HKG	USA	SVN	NLD	DEU	CHN	TUR	DEU + 2^{c}
Reference	[22]	[6]	[8]	[29]	[30]	[20]	[31]	[12]	[32]	[33]	[34]	[35]	[36]	[37]	[38]	[19]	[39]	[40]	[41]	[42]	[14]	[43]	[44]	[45]	[18]	[46]	[47]	[48]	[49]	[50]	[18]	[18]	[51]	[52]	[13]	[53]	[21]	[54]	[55]	[56]	[57]

C, Combination: variable studied together with other window properties, including all possible combinations.

I, Isolation: variable studied in isolation or in a limited number of combinations.

X: variable studied, either together with other properties or in isolation.

R/O/U: Residential/Office/Unspecified building used in study.

a: JPN, KOR, PHL, TWN; b: ESP, GBR, ITA, POL, ROU, RUS, SWE; c: ESP, SWE

Although not an exhaustive review, table 1 shows that the existing body of work is rather diverse. At the same time, however, the research appears heavily weighted towards small sets of certain properties. As an example of the most common choices, Persson, Roos & Wall [44] studied the energy balance influence of window area and glazing properties in low energy houses. They found that in a highly insulated building with low energy windows increasing window area has only little effect on heating energy use in a warm-summer continental climate. It was also noted, however, that even in a fairly cold climate the increase will necessitate shading or additional cooling in the summertime with south oriented windows. Later, Motuziene & Juodis [35] had similar results studying the same variables along with orientation in a similar climate, noting window area and orientation to affect cooling much more than heating. Vanhoutteghem et al. [20] added room area and width/depth ratio alongside these window properties in their study on window design in a nearly zero energy apartment building in a temperate coastal climate. Room geometry was found to affect suitable window solutions for thermal control and lighting especially in south-oriented rooms, even though the simulations only modeled an overcast sky. The importance of room geometry in relation to window design is further backed by earlier work by Susorova et al. [6]. They studied various combinations of window area, climate, room width/depth ratio and room area by simulating a single office room in different parts of the USA. The results showed that in terms of energy performance different orientations and locations favored different room and window geometry combinations.

Work on other window properties such as shape (here meaning width/height proportions), positioning on the wall and shading is much rarer, though not nonexistent. Bokel [39] studied the effects of window size and vertical position by simulating all combinations of the two using nine and three values respectively. Both were found to significantly affect the energy consumption of an office room in a temperate oceanic climate, although the effect of position naturally diminished with increasing window size. Using a residential room, Koohsari et al. [47] studied changes in vertical window position as well as window width and height, all separately. As the width and height studies didn't have fixed window area, the results mainly showed the effects of changing size. Still, it was noted that at least in their Mediterranean context height had more of an impact on energy consumption than width, indicating that shape itself also has an effect. On the other hand, simulations by Muhaisen & Dabboor [37] in a similar climate showed virtually identical results for two perpendicular windows regardless of size or solar orientation. The study didn't include utilizing daylight to reduce electric lighting. For shading, external solutions have been shown to have a significant effect on energy consumption even in heating dominant climates [33], especially with large windows [43].

As reflected by the above, and also noted by Kim et al. [38], most existing window-related work contains at most three concurrent variables. While this approach allows the easy optimization of those parameters, it obviously ignores possible differences in the results created by other co-occurring design decisions. Therefore, to gather realistic information there is a need to analyze the mutual effect of different design factors [8,38]. Such an approach obviously leads to increased complexity as well as requirements on the tools used. There have been efforts to study a large number of combinations through a reduced set of simulations. Kim, et al. [38], simulating a case in a temperate oceanic climate, employed a two-step design where they first defined the window to wall ratio (20%) with the biggest energy consumption difference between vertical window positions. After this, they studied the impact of solar orientation in all the different positions for this particular window size. Though the differences were rather minor, this process let them examine the solutions with the most noticeable effects without simulating all possible combinations. The study excluded windows' effect on lighting need, which might have had an effect on the results produced by window positioning [39]. Yong et al. [8] utilized a fractional factorial design to study ten building envelope design decisions including window to wall ratio, window U-value, solar heat gain coefficient, and solar orientation. Although this method did not allow them to seek individual optimal solutions, it did produce a comprehensive set of relative heating and cooling energy consumption impacts of various factors in a number of different USA climates. Contrary to many of the previous studies, solar orientation was found to have only a minor effect. This, however, could well be due to the case building having windows on three sides.

Overall, existing work on energy efficient window design appears heavily focused on optimizing window area and glazing properties. Conversely, there is little research on other architecturally significant aspects, such as window shape and positioning, and especially studying the various combinations of different properties. Most notably, the majority of existing work uses a very restricted set of variables, thus providing limited information on the possible interaction effects between different design decisions. The current paper addresses the above issues by including a number of window related architectural properties as independent variables and examining their combined as well as individual impact on heating, cooling and lighting energy consumption. Effects on for example visual comfort that were not specifically studied are considered in the discussion where relevant. The specific studied properties were chosen based on their significance for energy efficiency as noted by existing work, or alternatively the lack of existing work, and their close connection to architectural design. The primary focus is on properties which can be adjusted individually for each window regardless of the rest of the building.

1.2. Research objective

In accordance with the above, the main properties of interest in this study are as follows: window area, shape, horizontal position, external shading length, glazing properties, and apartment shape. Additionally, different orientations and geographic locations are included to address varying contexts. By including combinations of all studied properties, a more comprehensive picture will be achieved compared to studying different variables in isolation. Further reasoning behind the properties as well as their parameter values is presented in section 2.3. In accordance to the above, the main research question of the study is as follows: What is the effect of architectural window design decisions on heating, cooling and lighting need in Finnish climates?

2. Methodology

The research consisted of a simulation case study. To notice interaction effects between variables, the study was conducted using a full factorial experimental design, i.e. simulations were run for all possible combinations of the examined variables and their chosen properties. Three values for each variable were used to identify and consider possible quadratic relationships between the independent variables and energy consumption, previously found for at least window area (e.g. [21,29,54]).

The simulations were performed using IDA Indoor Climate and Energy (IDA ICE) v. 4.8 software. IDA ICE simulates both energy consumption and indoor climate using adaptive time steps, thus giving more accurate results than for example a calculation method relying on monthly averages, which is commonly used in Finland for proving adherence to regulations when there’s no mechanical cooling. Importantly for this study, the software uses realistic weather data with both clear and overcast days and can adjust lighting gradually based on the amount of natural light, both direct and diffuse. Multiple validation tests have been performed for IDA ICE, showing it to give values in line with other commonly used simulation software such as DOE-2 and TRNSYS [58–62]. For this study, the building models used were first created in Graphisoft ArchiCAD 19.0 for the various window geometries, and then further adjusted in IDA ICE to form the full set of variants.

2.1. Defining the case apartment

The case used for the simulations in this study was a typical single resident apartment in assisted living for the elderly. Assisted living was chosen instead of regular housing due to the repetitive nature of the apartments (also noted by Palviainen [63]), relatively strict indoor conditions requirements [16,26], importance of architecturally successful window design [26], and easy availability of material from construction supervision offices. For the studied properties, these apartments are very similar to regular studio apartments in the rest of the Finnish stock [64]. The main room is typically very similar in size between the two, and almost exclusively opens in only one direction. Additionally, as one and two person households become ever more prevalent across all age groups, the apartment size requirement difference between elderly and regular housing is likely to diminish. Currently, 43.3% of Finnish households reside in a studio or one bedroom apartment [65]. A single room was chosen for the study to both better isolate the results from the design decisions in the rest of the building and keep the simulation times manageable. A sample of actual apartments was used as the basis to ensure more realistic dimensioning compared to a fully fabricated shoebox model.

The base case apartment was defined from the architectural drawings of 1421 apartments in 108 group home units in 28 Finnish assisted living facilities, from the three largest cities in Finland; Helsinki, Espoo and Tampere. The apartment was assumed to be located away from the edges of the façade, meaning that heat transfer through the interior walls and interior door is set to zero. The apartment's total floor area (25 m^2) is an average of all the apartments and includes the bathroom, for which a typical compact accessible design was used, and the bathroom wall. Due to the limited area and required accessible dimensioning, there was very little variation in the spatial arrangements of the apartments in the sample. The floor to ceiling height was set at 2500 mm, which is common practice and the legal minimum in Finland [66]. Of all the single resident apartments in the sample (N=1421), 52.5% (n=746) only had one window. This most common case was used in the study. The exterior surroundings are assumed open enough to exclude possible shading, reflected light and wind tunnel effect from neighboring buildings and vegetation.

Figure 1 shows the average, base case apartment, on which the different variants are based (see section 2.3. Variable properties). The simulated apartments were modeled unfurnished, and lighting was considered to the extent of maintaining an even lux level of general illumination. Furniture layouts and corresponding localized lighting might have some effect on the results, as might large furniture itself, but such study is outside the current scope aside from being noted in discussion. As the bathroom does not have a window and is separated from the main room by a door, it was excluded from the simulation.

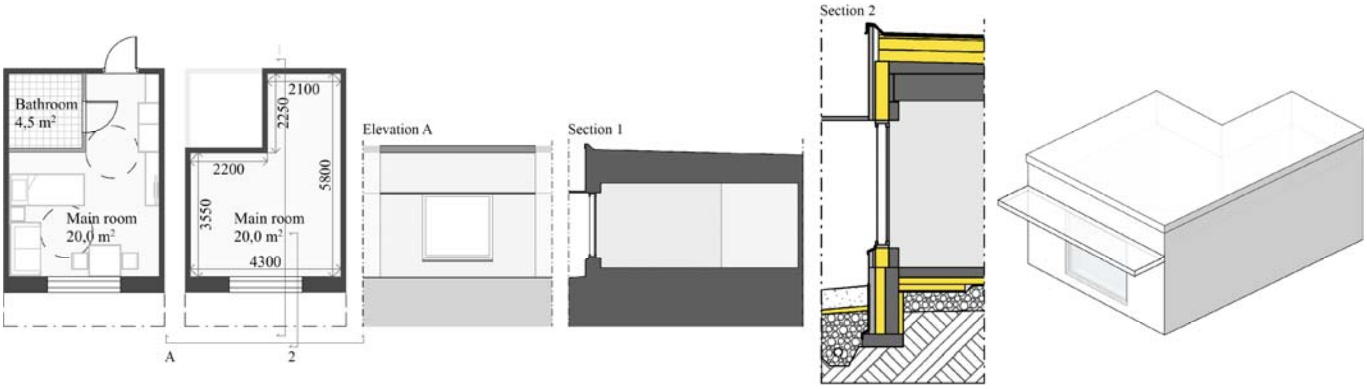


Fig. 1. Average apartment defined from the research sample: illustrative floor plan, simulated floor plan, elevation, apartment space section, exterior wall/roof/floor section with structural and insulation layers, and isometric projection.

2.2. Constant properties

Table 2 summarizes the constant properties, i.e. those that are the same in all of the simulated variants, excluding aspects of apartment geometry already described above. The technical properties of the apartment as well as the desired indoor climate conditions follow the Finnish building code [16,67]. Acceptable interior temperature ranges for thermal comfort as decreed by the Finnish Ministry of the Environment are 20–25 °C during the heating season and 20–27 °C during other times—the heating and cooling set points of 21 and 25 °C are given in the Finnish building code for conducting energy use calculations in the chosen building type [16]. During the time of this research, the Finnish building code [67] was updated. For this study, the only difference would be in the heat recovery temperature ratio, for which the reference value was changed to 0.55 [16]. Using the higher value would have reduced the resulting heating need somewhat. For lighting, daylight control was used, i.e. lighting power was adjusted based on available natural light. In addition, the lights were only on in the morning and in the evening, when the resident is present and not sleeping. The simulation counts all lighting energy consumption as internal heat gain. As there was no kitchen and the bathroom was not included, water use was assumed to be zero. Changing this could affect the apartment's internal heat load and total energy consumption [16], but with typical use is unlikely to significantly affect evaluating the chosen variables.

Table 2. Constant properties and their values used in the study.

Property	Value	Source/note
Exterior wall, floor and ceiling U-values	0.17, 0.16, 0,09 W/(m^2K)	[16,67]. No heat transfer through interior walls and door.
Exterior wall, floor and ceiling air infiltration (q_{50})	2.0 $m^3/h/m^2$ at 50 Pa	[16,67].
Ventilation air flow rate	0.5 $dm^3/(s\ m^2)$	[16,67]. No natural ventilation aside from above air infiltration.
Heating/Cooling method	Ideal heater/cooler	A measure of the overall heating/cooling needs within the simulated zone. No energy use outside the zone.
Heat recovery temperature ratio	0.45	[67].
Heating and cooling set points	21 °C, 25 °C	[16,67].
Ceiling, wall, and floor reflectances	70%, 50%, 20%	[68].
Target illumination level	300 lux	[68–70]. Even lighting across the room, measured at the height of 800 mm.
Lighting power and schedule	6 W/m^2 6:00–8:00, 18:00–22:00	Maximum power for 300 lux, automatically adjusted based on daylight level and lights being switched off.
Internal heat gains from people	125 W (18:00–8:00)	[16]. Time when the resident is present adapted from standard occupancy for residential building.
Internal heat gains from appliances	2.7 W/m^2, (53.6 W total)	[16]. Constant heat gain, does not include lighting.

2.3. Variable properties

The variable properties examined in this study as well as their studied parameter values are presented in table 3, divided into main and context variables based on their role in the study. The main variables are the primary focus of the study, while considering the context variables is vital for the applicability of the results. The reasoning behind both the variables chosen and their parameter values is detailed in the following subsections.

Table 3. Variable properties and their values used in the simulations.

Main variables						Context variables	
Window area (m^2)	Window proportions[a]	Window horizontal position	Window shading length (% of window height)	Window glazing properties	Apartment proportions (W/D-ratio)	Climate (cities in Finland, lat./long. coordinates)	Façade orientation
2.0	Narrow	Left	0.0	U-value 1.00, g-value 0.40	Narrow (0.49)	Helsinki, 60.19/24.95	South
4.0	Average	Center	50.0	U-value 0.60, g-value 0.30	Average (0.75)	Jyväskylä, 62.24/25.75	West
6.0	Wide	Right	100.0	U-value 0.60, g-value 0.50	Wide (1.55)	Sodankylä, 67.42/26.59	North
							East

a: The specific window dimensions vary based on window area. The narrow variant is always 2500 mm tall and the wide variant is always 3500 mm wide.

2.3.1. Window area

Window area is the single most studied property in existing work (see table 1). Lylykangas et al. [70] placed it in the top three factors influencing the cooling need of buildings in Finland. Even more recently, Yong et al. [8] found window to wall ratio to be the building envelope design factor most impactful on both heating and cooling in all their eight studied climates. Although some previous work suggests that the influence of window size diminishes as buildings' energy performance in general gets better [44,54], it must be included here for both architectural and energy efficiency reasons. Furthermore, the property is especially interesting for a multivariable study: it has been noted to affect various other properties such as need for shading [44] and the effect of window proportions [39], and its own effect also depends on at least climate and orientation (e.g. [6,19,35]).

For this study, average window area was defined as the arithmetic mean of total window area per apartment. Areas from secondary and tertiary windows were combined into the single simulated window. This reduces thermal bridging compared to having multiple windows, but represents the most common case of there only being a single window and simplifies forming the model as well as interpreting the results. The presented figure describes the whole window, including the frame and other opaque parts (the width of which is fixed at 100 mm), so the actual glazing area varies slightly based on window proportions. The smaller variant is half the size of the average and also roughly the legal minimum in Finland [66].The larger variant is correspondingly bigger and simultaneously near the maximum for accommodating all the combinations of window and room shape.

2.3.2. Window proportions

Existing studies that include the impact of window proportions are very few and fairly inconclusive. Of the two found when preparing this study, one did not allow evaluating the impact of shape alone [47] and the other did not consider lighting [37].

Here, the effect of shape is studied through rectangular windows of different width and height. Shape in the sense of complex form might have an effect through heat bridging and propensity to installation errors but has been excluded from the study as proportions are a more common consideration in practice. The narrow window proportions variants reach from floor to ceiling (2.5 m), while their width varies based on the concurrent window area value. Similarly, wide windows reach the full width of the narrowest apartment (3.5 m), to make the same window sizes usable in all of the calculations, and vary in height.

2.3.3. Window horizontal position

No existing research was found on the energy effects of windows' horizontal positioning. Similarly to vertical positioning, the distance of a window from the corner of a room should affect light distribution inside. Depending on the severity of this effect, the result could have direct practical consequences on the suitable locations of various functions in the room. Vertical positioning has been shown to have some effect, primarily through lighting [38,39,47]. In practice, however, it cannot be varied much for the main window of a living room type area due to view requirements. Because of this and a lack of previous work, varying the horizontal position was chosen for this study. The three window positions simulated here are the center of the apartment's façade wall and both adjacent corners, always centered vertically.

2.3.4. Window shading length

Several researchers have noted the importance of shading in finding a balance between beneficial and excessive solar heat gains [12,36,42,43,52,54], even in heating-dominated climates such as in Finland [57]. In contrast to interior blinds or curtains, external shading helps keep the view outside. It also keeps excessive heat from entering the building envelope in the first place, instead of reflecting it back from inside the window or the apartment. Thus, external shading is more effective against overheating especially from high sun angles, although for example blinds are still beneficial to reduce glare and possible excessive heat gain when the sun is low.

In this study, shading was modeled as solid, fully opaque horizontal overhangs—comparable to for example a balcony slab or eaves in addition to specific shading devices. The overhangs spanned the width of the apartment and their length was defined as a percentage of the window opening's height. Blinds or curtains were not modeled.

2.3.5. Window glazing properties

Window glazing properties are a close second to window area for the most included window design factor in existing work (see table 1). They have mainly been approached through varying—possibly among other parameters—the windows' thermal transmittance [8,12,18–20,42], solar transmittance [12,14,19,22,32,35,41], or most often both simultaneously[8,12–14,19,20,22,29–32,35,36,41,42,50,51,57]. Some studies have included both single and multiple parameter variation. This extensive body of research has shown glazing choice to have an impact on the effect of a wide range of other properties, thus making it essential to include in a multivariable study.

Three different combinations of U-value (thermal transmittance) and g-value (solar transmittance) were chosen for this study to represent typical modern construction, in the order presented in table 3: the current Finnish reference values in new construction [16], a low-U window with a typical g-value, and a low-U window with a high g-value. The U-values presented are for the whole window, glass and frame combined. Thus, the specific values for glass and frame differ slightly based on the size and shape of the window and accordingly the ratio of frame to glass.

2.3.6. Apartment proportions

Apartment shape is closely tied to window design, from the viewpoints of heating, cooling and lighting as well as views [6,20,48,49]. For example, shallow layouts require less window area for natural light to reach the rear of the apartment, but simultaneously require a wider spread of windows. A wider apartment also has more façade area than a narrow apartment with equal floor area, and thus more heat transfer through this wall. This could skew the results somewhat, if one assumes that in a complete building the depth of the building frame would be the same regardless of apartment geometry. In practice, however, it is likely that with wider apartments the whole building would have more façade surface area due to most of the other spaces also requiring windows.

The simulated apartment shapes were formed based on static floor area and varying width/depth ratios. Width/depth ratios were determined as the arithmetic mean from all apartments used to define the average case, and narrowest/widest 5% for the respective variants. Width was measured along the facade wall. If there were multiple facades, the one with the most window area was considered the width dimension. The dimensions were taken from the furthest corners of the apartment, ignoring possible small niches in the walls (deviation at most 0.6m, a typical depth for fixed closets). Non-rectangular apartments (9.4% of all apartments) were excluded from this measuring, as their figures would not have been applicable. No connection was identified between apartment size and shape in the sample. Thus, the shape characteristics should be applicable regardless of floor area.

2.3.7. Climate

To capture a wider context, many existing studies have included climate comparisons of varying scope (see table 1). It has been noted to affect the results for at least apartment or room shape [6], window area [6,8,19,22,29,30,32,48], external shading [12], and glazing properties [8,13,14,19,29,30,32,50]. For this study's simulation locations, three cities from different parts of Finland were included to better cover the various climates present in the relatively long country and increase applicability to other countries. These are, from southern to northern Finland: Helsinki (coastal, warm-summer humid continental), Jyväskylä (inland, subarctic), and Sodankylä, (inland, subarctic). Information on local temperature conditions is presented in Table 4 and solar charts in figure 2.

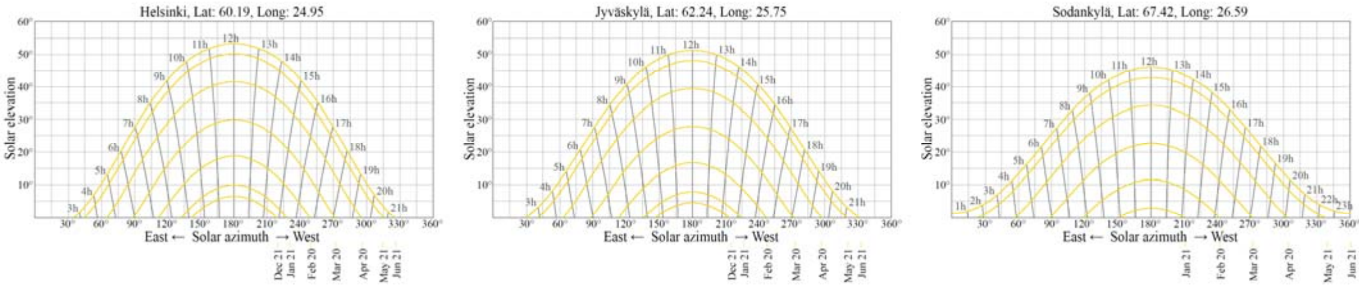
Table 4. Temperature information for the studied locations [71].

Location	Heating degree days (2018)[a]		Cooling degree days (2018)[a]		Record high °C (1981–2010)	Average high °C (1981–2010)[b]	Average low °C (1981–2010)[b]	Record low °C (1981–2010)
	Base 17 °C	Base 21 °C	Base 17 °C	Base 25 °C				
Helsinki	4060.7	5324.0	304.7	27.6	33.7 (Jul)	22.5 (Jul)	-8.1 (Jan)	-35.9 (Jan)
Jyväskylä	4691.5	5983.5	260.1	22.7	34.2 (Jul)	21.8 (Jul)	-12.7 (Jan)	-38.5 (Jan)
Sodankylä	5823.7	7172.7	174.0	20.3	32.1 (Jul)	19.4 (Jul)	-19.6 (Jan)	-49.5 (Jan)

a: In Finland 17 °C is typically used [72], 21 and 25 °C correspond to the heating and cooling setpoints in the regulations and this study [16,67].

b: Average high and low temperatures are listed for the warmest and coldest month respectively.

Fig. 2. Solar charts for the studied locations [73].



As can be seen, especially between Helsinki and Sodankylä there is a rather large difference in temperature variation and thus the expected heating and cooling needs between the locations (table 4) as well as in the availability and angle of sunlight (figure 2). The simulation uses localized hourly temperature and solar data for the year 2012 from the Finnish Meteorological Institute.

2.3.8. Façade orientation

Façade solar orientation is extremely often included in existing window research (see table 1), and for good reason. It has been shown to be connected to the impact of at least the following properties: climate [6,29,52], apartment/room shape [6,20], window area [31,33,35,42,49,53], window position [38], external shading [33,36,52], and glazing properties [20,29,34,50,51]. Therefore, in this study each of the cardinal directions was included.

3. Results and discussion

The numerical simulation results are presented as heating, cooling, lighting and total energy need in the studied apartment, total being the sum of the previous categories. System losses outside the apartment were excluded, meaning that for example heating energy consumption is exactly the same as heating need. The discussion proceeds from the main variables to overall findings.

In addition to studying the numerical simulation results directly, regression models were formed in IBM SPSS Statistics 25 using the multivariate general linear model. Separate models were formed for each climate using otherwise identical specifications. The models included all main effects, as well as interaction effects between solar orientation and each of the other independent variables. Adjusted coefficients of determination (R^2_{adj}, the proportion of variance in the result predictable from the independent variables) for each combination of climate and energy consumption category are presented in table 5. The residual plots for the same combinations are presented in figure 3. P-values for each combination of climate and energy consumption category were <0.001. As reflected by table 5 and figure 3, the model was very accurate for heating and lighting need aside from extreme values, and somewhat less for cooling and thus total energy consumption, tending to underestimate the results for the latter two. The linear regression results are primarily used to present mean energy consumptions for each main variable in figures 4–9.

Table 5. Adjusted coefficients of determination (R^2_{adj}) for the dependent variables of the formed linear regression models.

	Helsinki	Jyväskylä	Sodankylä
Heating	0.972	0.972	0.972
Cooling	0.747	0.679	0.644
Lighting	0.989	0.990	0.991
Total	0.879	0.917	0.956

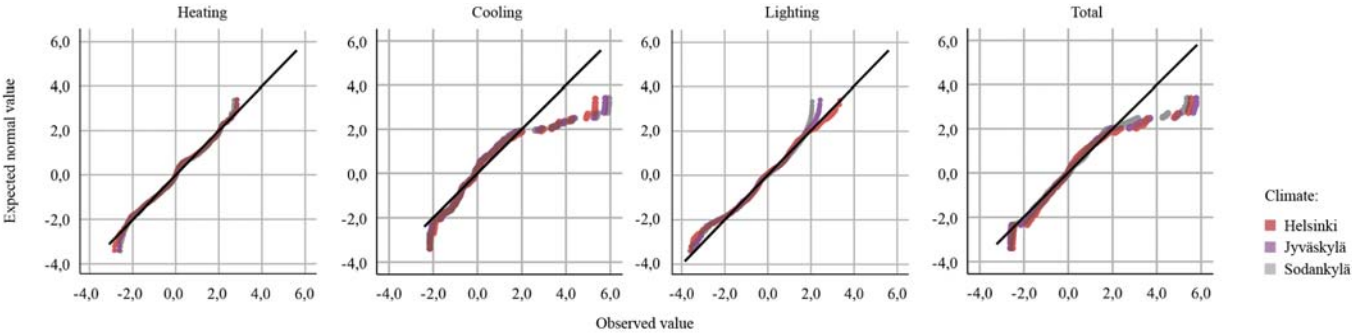


Fig. 3. Studentized residual plots for the dependent variables of the linear regression models.

3.1. Main variables

This section first discusses the effects of each of the main variables. As the goal of the research was to study the combined effects of various design decisions, this includes connections to other variables where relevant—the categorization merely acts as a clarifying framework. After the individual main variables, the discussion continues into more summarizing observations.

3.1.1. Window area

Figure 4 shows the mean energy consumption for different window areas (2, 4, and 6 m^2) in the studied climates and solar orientations. The accompanying bars represent the total range of values for each combination of climate and orientation. Accordingly, the size of the area covered by the mean values in relation to the underlying bar corresponds to the size of the effect window area has in each context and energy consumption category. The same principle also applies to figures 5–9. In general, increasing window area increased heating and cooling energy consumption but reduced lighting energy consumption. On average the reduction in lighting need was only 18.9% of the combined increase in heating and cooling need going from small to medium (2 m^2 to 4 m^2), and 13.1% going from small to large (2 m^2 to 6 m^2), thus leading to an increase in total energy consumption. The above general trend, however, did not apply to all cases. Depending on the parameter values of other variables, the change in heating need was between -4.8 to 14.6% (average 5.7%) going from small to medium and -5.3 to 28.5% (average 12.3%) going from small to large; the change in cooling need was -1.3 to 453.7% (average 90.7%) going from small to medium and 0.8 to 1221.1% (average 257.4%) going from small to large; the change in lighting need was -4.7 to -15.5% (average -10.9%) going from small to medium and -10.6 to -22.9% (average -17.5%) going from small to large. Thus, increasing window area could either increase or decrease heating and cooling needs, and always decreased lighting need. The effect on heating need was greatest in cold climates and northern orientations, while the opposite was true for cooling. The effect on lighting was not significantly affected by climate, although the different solar angles and daytime durations had some effect. Notably, in the warmest studied climate of Helsinki large windows had their highest mean and overall energy consumption when facing east or west instead of north, due to the high cooling need.

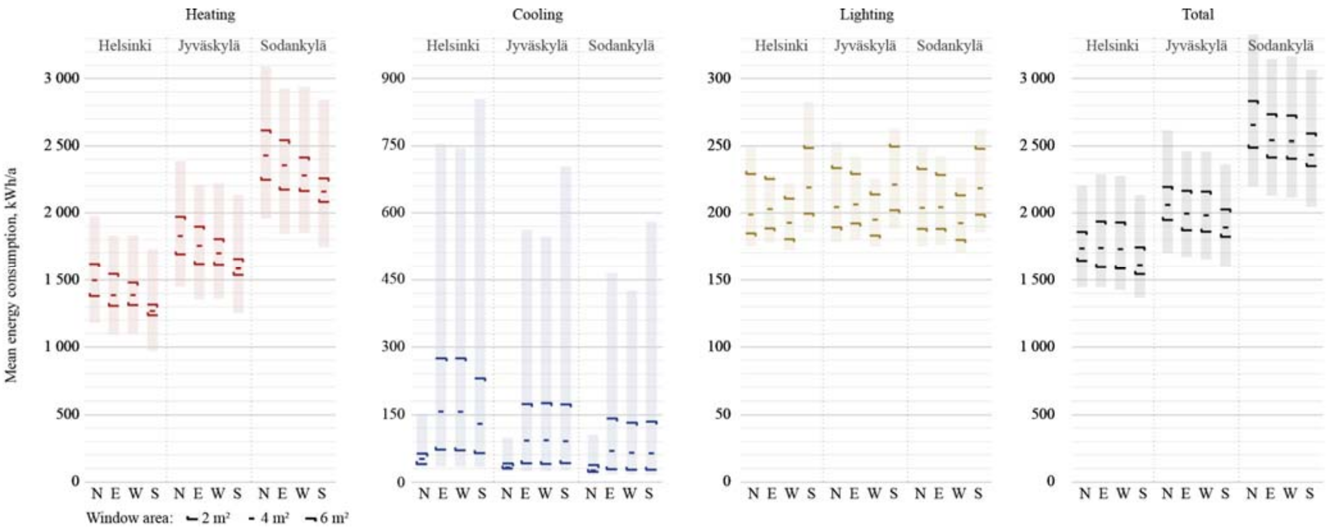


Fig. 4. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of window area. Bars represent total range of values.

Keeping all other properties fixed, increasing window size from 2 m^2 to 4 m^2 was only beneficial in 2.1% of the cases, and from 2 m^2 to 6 m^2 in 0.1%. At the same time, sorting all cases by total energy consumption and studying the top 5%, a fifth of them had 4 m^2 or 6 m^2 windows. The above shows that increasing window size can increase energy efficiency, but the effect is highly dependent on other properties such as shading and glazing properties and requires them to be adjusted accordingly. This is further supported by the observation that the cases with least heating need in the warmer climates of Helsinki and Jyväskylä had medium sized south facing windows with high g-value glazing and no shading. Only in the coldest climate of Sodankylä was heating need lowest with the smallest windows.

Overall, when comparing cases with the least heating need, increasing window size by one step in any of the climates only increased heating need by approximately a single percent. Due to the corresponding increase in cooling need, however, all of the large window variants were far from being the best overall performers. It can therefore be deduced that the most energy efficient choice would be combining medium to large sized, high g-value windows with controllable shading to avoid overheating during the warm season. The results are similar to previous work (e.g. [43,44]) and suggest that Finnish and similar climates, though heating dominated, do not necessitate minimizing window area to achieve energy efficient results especially in the southern parts. Correspondingly, it is vital to consider possible cooling need even in northern locations, especially in well insulated buildings with large window areas with orientations other than north. Whether mechanical cooling is actually required in practice depends on the desired interior conditions and other strategies for managing overheating such as utilizing thermal mass and ventilation by opening windows.

3.1.2. Window proportions

Window proportions had practically no effect on calculated energy consumption, as shown by the nearly fully overlapping variant symbols for each context in figure 5. The largest difference in total energy consumption found between the narrow and wide variants was less than a percent. Despite the entirely different climate, the results echo those had by Muhaisen & Dabboor [37] in Gaza.

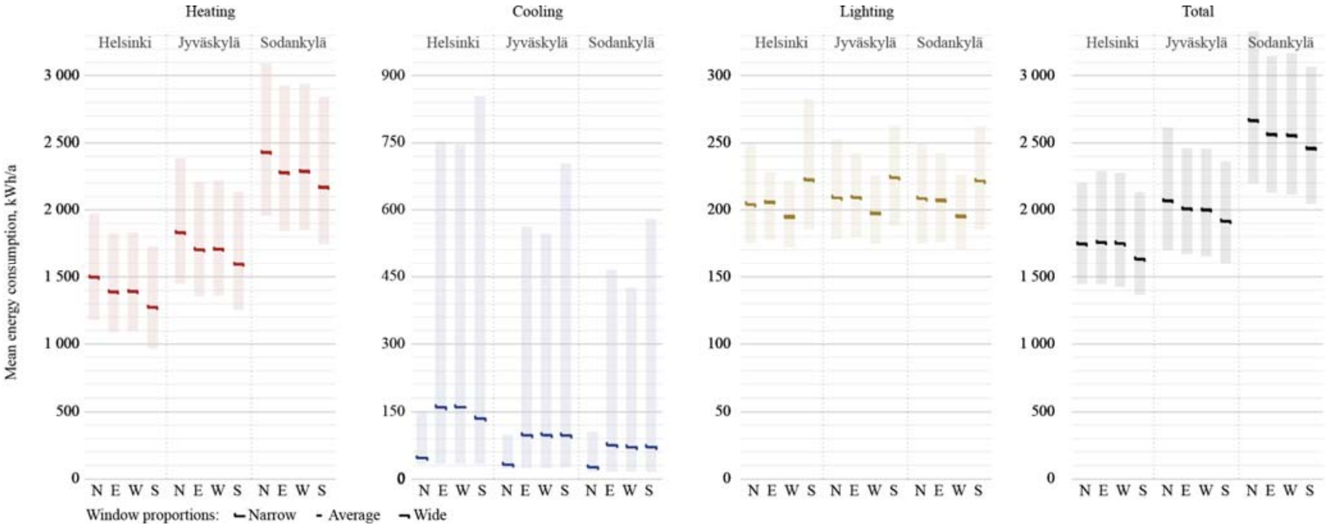


Fig. 5. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of window proportions. Bars represent total range of values.

As the effect on calculated energy use was marginal at best, decisions can be made primarily from the perspectives of usability, such as furnishability and views, and aesthetics. Especially with high U-value windows this also includes considering where users will spend time in the room, so as to avoid indirect energy efficiency effects from temperature differences near the window and the resulting adjustment of heating or cooling of the whole room.

3.1.3. Window horizontal position

Like some existing research has noted for window vertical position [38], horizontal position also had no significant effect (see figure 6, largest impact being 0.24% of total energy consumption. The average results are influenced by the wide window variants having little room to move in narrow apartments but considering the overall lack of effect the fact appears insignificant.

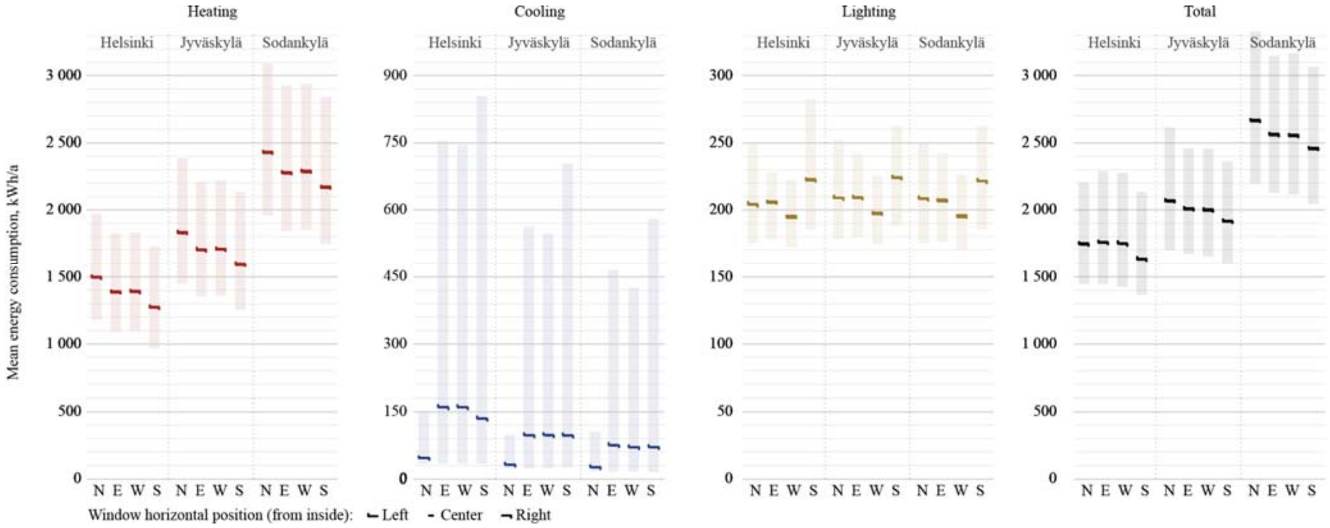


Fig. 6. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of window horizontal position. Bars represent total range of values.

Based on the results, without specific condition requirements for different parts of the room window position can be decided primarily on grounds other than energy consumption. The issue of temperature near the window possibly being different from the rest of the room also applies here, however, as does the need to consider the amount of light required and wanted in different areas of the space in practice—specific work area locations can have an effect [39]. For visual comfort some activities such as watching TV might require using blinds or curtains to prevent glare, while for example dressing might not, again leading to indirect impact on utilizable solar heat and natural light. Thus, the concrete effect of architectural design decisions here could be significantly larger than calculations show.

3.1.4. Window shading length

Adding fixed shading increased heating and lighting need, reduced cooling need and as a result on average had a rather small effect on total energy consumption (see figure 7). The advantage of adding shading length was logically greatest when there would otherwise be major cooling need. For example, in the case of large, south facing windows in Helsinki going from no to long shading only reduced total energy consumption by 0.5% with low g-value glazing, but with a high g-value and thus high solar heat load the change was 35.5%.

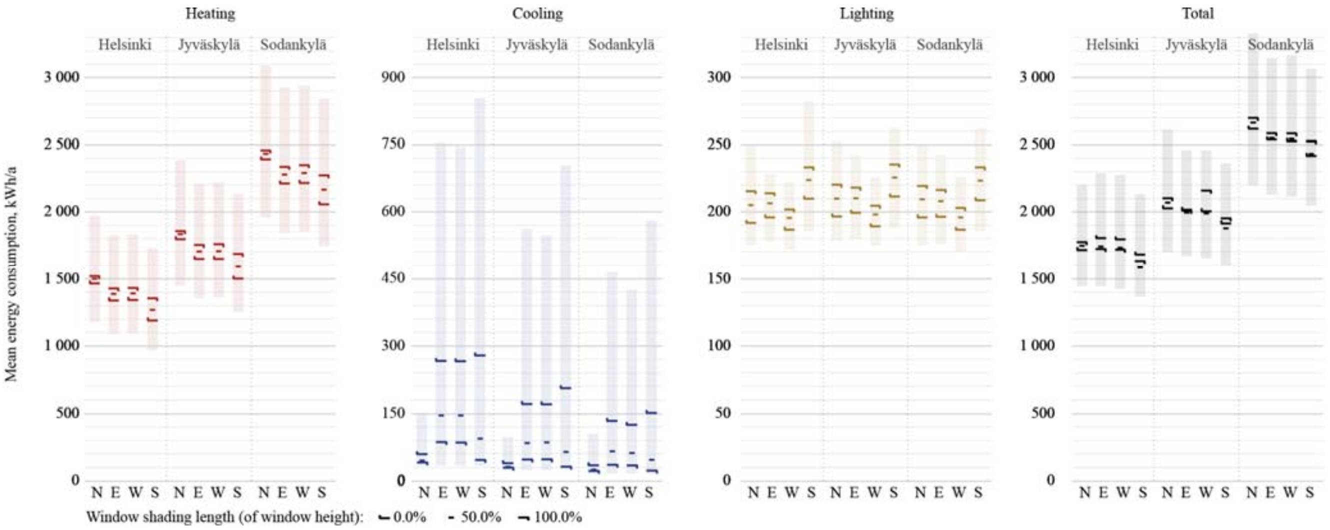


Fig. 7. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of window shading length. Bars represent total range of values.

As noted in section 3.1.1. Window area, fixed shading is always a tradeoff between different areas of energy consumption. Adding shading increased heating and lighting needs in all studied the cases. The increase in heating need was between 0.5 to 8.4% for mid-length shading (50% of window height) and 0.8 to 18.8% for long shading (100% of window height), averages being 3.7% and 7.0% respectively. The increase in lighting need was between 3.9 to 92.9% for mid-length shading and 6.3 to 190.7% for long shading, averages being 32.4% and 60.2%. At the same time, adding shading almost always (in 99.7% of cases) decreased cooling need: between 0.1 to 81.5% for mid-length shading and 0.1 to 95.1% for long shading, averages being 41.7% and 54.2%. Compared to the 2916 unshaded cases, a beneficial effect on total energy consumption was achieved in 36.2% by adding mid-length shading and in 26.1% by adding long shading—i.e. in these cases the increase in heating and lighting needs was smaller than the decrease in cooling need. Correspondingly, in 37.6% of the cases adding shading increased energy consumption. This is in contrast to previous results by Apte, Arasteh & Huang [12] who found external shading to always increase total energy consumption in their studied heating dominated climates. Cases with highest cooling need expectedly benefitted from shading most often: in Helsinki mid-length shading reduced energy consumption in 53.6% of the cases, and long shading in 42.0%. For Sodankylä, the respective figures were only 21.3% and 12.7%. Windows oriented south benefitted from shading in 63.4% of the cases—a result similar to those had by Košir, Gostiša & Kristl [43] and suggested by Persson et al. [44]. Of windows oriented north, only 1.2% benefitted from shading, and even then the benefit was on average only 0.3%. Based on the above, while there is high variability depending on other design decisions, in general fixed shading appears to have a positive effect even in northern locations for large, high g-value windows in warm orientations. Conversely, when there is already very little cooling need due to window size or especially orientation or glazing properties (see section 3.1.5) the effect is either nonexistent or negative.

The results regarding tradeoffs between heating, lighting and cooling need indicate that an optimal choice of exterior shading from a performance perspective would be a system that constantly reacts to the current conditions. This kind of a system of course also raises the issues of cost and added maintenance, but even an on/off-solution based on the local heating season has been found beneficial [43]. Suitably placed deciduous trees can also perform the function of adjustable shading to a degree. Internal shading, such as blinds or curtains, can have similar results to external, with more limited ability to prevent heat entering the building envelope and more restriction on views. In practice a degree of internal shading would likely also be needed to prevent glare with low sun angles, even if overheating were not an issue.

3.1.5. Window glazing properties

All other variables equal, the two low U-value windows outperformed the high-U variant in 97.1% of cases. In the remaining 2.9% exceptionally high cooling need caused the higher heat losses to appear beneficial. Corresponding to the amount of heat losses, the impact of U-value was more significant in a cold climate, but was not much affected by orientation, as shown by the rather equal distances between the first and third variants within each climate in the heating need plot in figure 8. Of the two low-U windows, with other properties fixed the higher g-value version performed better in cold orientations and climates and vice versa, due to the lower heating and higher cooling need. Large, unshaded high-g windows were most sensitive to solar orientation due to changing cooling need. Correspondingly, changing any of the above reduced the effect of orientation. A high g-value reduced lighting need but the effect was minimal.

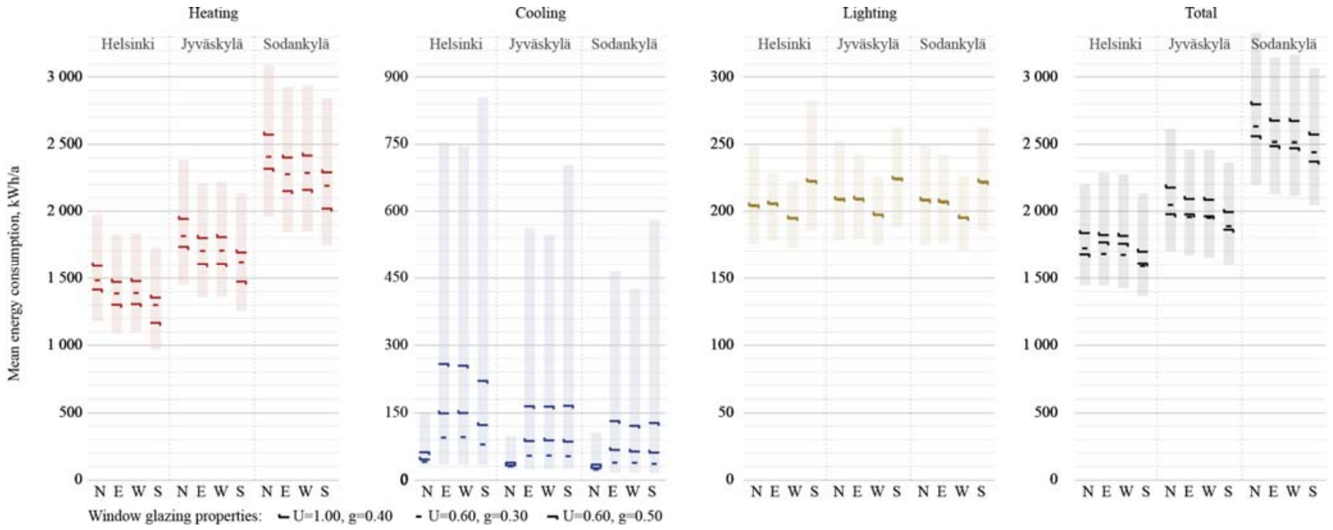


Fig. 8. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of window glazing properties. Bars represent total range of values.

For heating, cooling and total energy need, high-g windows with long shading achieved very similar results to low-g windows with no shading in all climates and orientations. The largest differences were observed in Helsinki (8.0%) and Jyväskylä (3.0%) with large south facing windows, most other comparison pairs having a difference under 1%. Therefore, it appears that from an energy perspective a choice can rather freely be made between adding shading elements or using low-g windows, as suggested before by Ebrahimpour & Maerefat [36] for the vastly different climate of Iran. The finding implies increased freedom of choice in architectural design but does not of course remove the need to consider for example glare resulting from direct sunlight. While a low U-value was found to be always beneficial, the difference between the climates indicates that in relatively warm locations controlling overheating through g-value or shading should be prioritized if compromises must be made. When there is no risk of overheating, such as with northern orientations, g-value should be maximized to best utilize solar heat gains.

3.1.6. Apartment proportions

The effect of apartment proportions resulted almost exclusively from heat losses through the façade, leading to wide apartments having higher heating and total energy consumption, and lower ones for cooling and lighting, aligning with findings by Susorova et al. [6]. Correspondingly, as shown in figure 9, climate had a large effect on the variable's effect on heating, cooling and total energy consumption, while orientation did not: there is very little variation in the difference between the mean values between orientations.

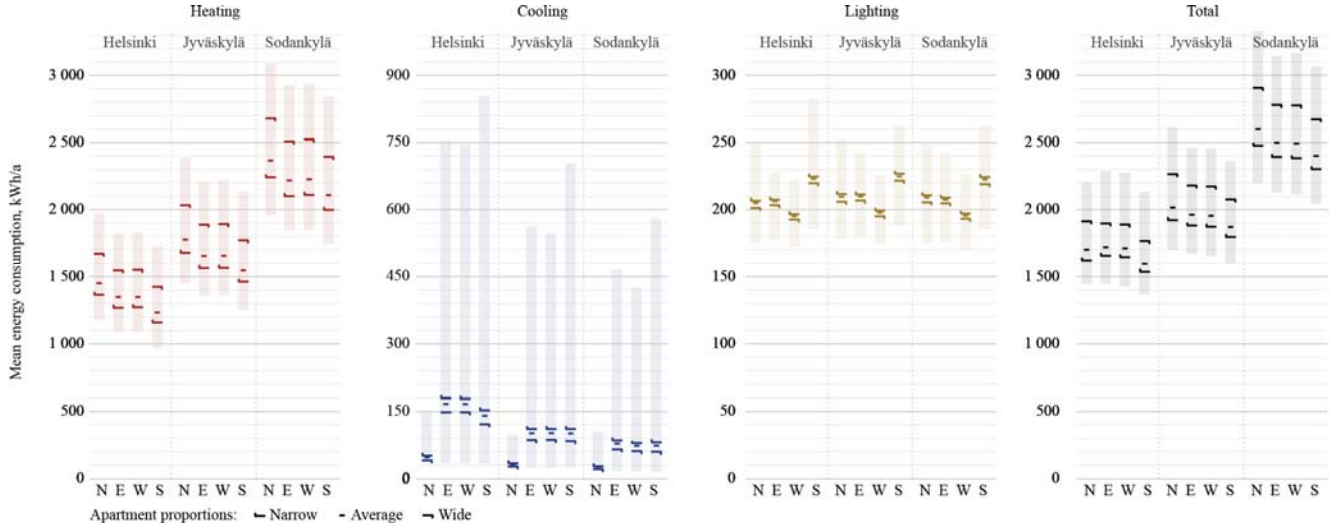


Fig. 9. Mean heating, cooling, lighting and total energy consumption by climate and solar orientation for different values of apartment proportions. Bars represent total range of values.

The difference in total energy consumption between a narrow and wide apartment was 4.4 to 17.3% in Helsinki, 5.6 to 17.1% in Jyväskylä and 7.9 to 16.6% in Sodankylä, average difference being approximately 14% in all the climates. Comparing otherwise identical cases, lighting need for the wide rooms was 0.2 to 5.8% lower than for narrow ones, averaging 2.0%. The results suggest that the ratio of a building's area or volume to its envelope area, the shape factor, has a role in its overall energy consumption, especially in a cold climate, but mainly affects the energy efficiency impacts of window design decisions through lighting need. As with window proportions and position, however, actual use of the space and specific requirements in different parts of it could have indirect effects.

3.2. Overall findings

In all of the cases the majority of energy consumption came from heating, although the proportion varied greatly (48.6 to 93.7%, average 85.1%). The share of cooling need varied between 0.5 to 42.1%, averaging 4.5%, and lighting between 5.5 to 18.6%, averaging 10.4%. Heating and cooling needs as percentages of total energy consumption had a strong negative correlation (Pearson's *r* -0.95 in Helsinki, -0.92 in Jyväskylä and -0.90 in Sodankylä), indicating that solutions which increased one decreased the other. This is also somewhat visible in the leftmost scatterplot of figure 10, in the curved L shape of each series.

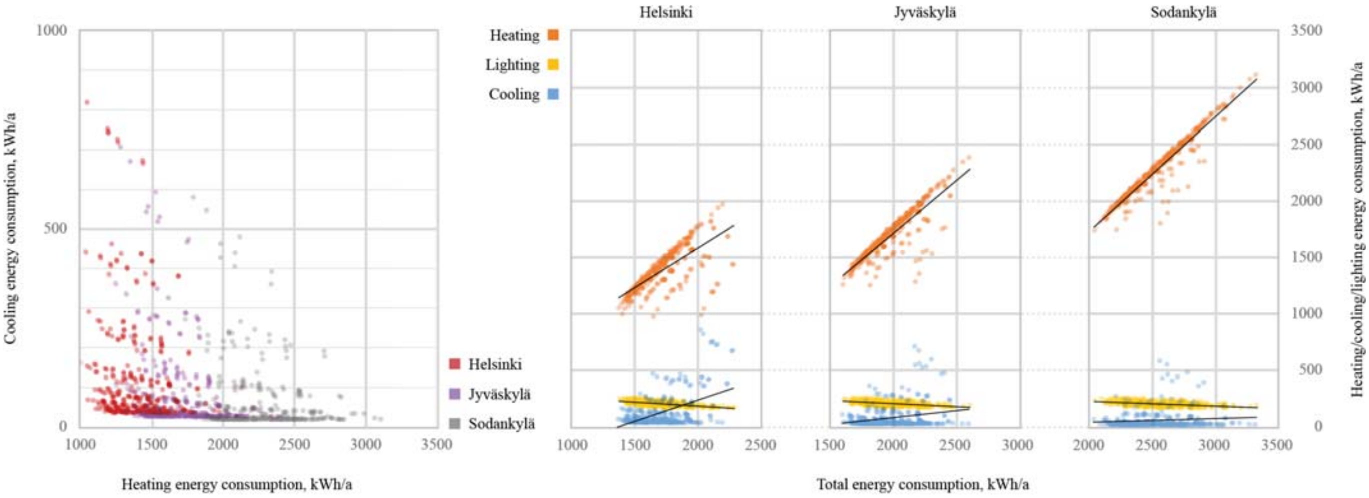


Fig. 10. Heating versus cooling energy consumption of all simulated cases (left) and heating, cooling, and lighting energy consumption of all cases by climate (right).

A similar observation can be made from the three rightmost plots, where progressing towards a colder climate shows a strengthening correlation for total energy consumption and heating, and a weakening one for total energy consumption and cooling. Thus, from a design perspective the focus should correspondingly shift towards minimizing heat losses and maximizing heat gains if compromises must be made.

There were, however, cases with high cooling need in all three climates and all façade orientations except north, as also shown in figure 11. Unlike with heating need, where Helsinki's highest values barely overlap with the lowest of Sodankylä, the ranges were also comparatively similar for the different climates. This highlights the need to take possible overheating into consideration even in cold locations: while moving further north might be considered an automatic increase in heating need, the opposite is not necessarily true for cooling.

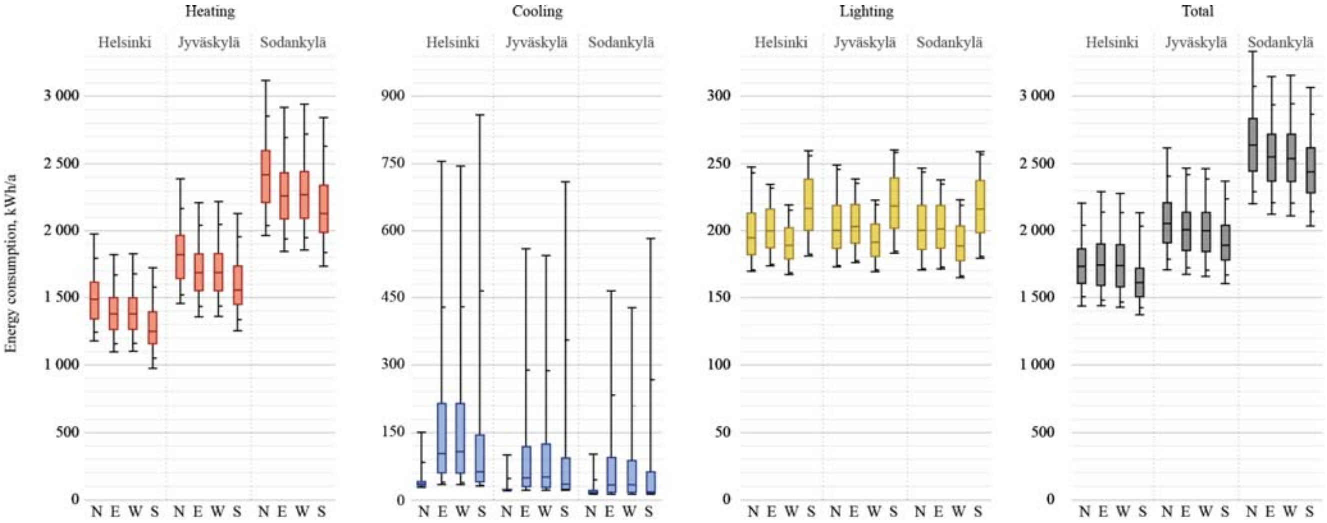


Fig. 11. Energy consumption for the studied combinations of climate and façade orientation: interquartile (box), 90% (single sided dash) and total (full whiskers) ranges.

Among all the cases, heating and lighting needs were fairly evenly distributed, while cooling need was heavily weighted towards the lower end of the ranges with approximately 90% of the results landing in the bottom halves. In relation to this, and due to the vastly different absolute ranges of heating and cooling, total energy consumption ranges for each combination of orientation and climate were rather close to the corresponding heating needs. A notable exception, however, is Helsinki, where due to significant cooling need the cases with highest total energy consumption were oriented east and west instead of north. In these cases, the northern orientation still had highest heating need, but not by enough to offset the difference in cooling need. Orientation in general had a large effect on nearly all variables, as in most—although not all (e.g. [6,8])—previous studies.

Lighting need had very little variation between the three studied locations despite different day lengths and sun angles. Much of this was likely due to the schedule used, which also led to the southern orientation having the highest need for artificial lighting. In figure 10 a slight inverse correlation between lighting and total energy consumption can be seen. Probable causes for this are the southern orientation mainly having the lowest total energy need and, conversely, combinations like large, unshaded windows having high total energy need. With more continuous lighting, especially at higher lux levels and thus energy consumption, the southern orientation would likely have fared better, as would have some of the larger and less shaded window variants. However, the resident not being present 8:00–18:00 is rather comparable to a normal workday with errands and hobbies, so the situation is not entirely unique to elderly housing.

Even though for example cold conditions favored modest window sizes and shading towards south tended to be beneficial, no single design decision was found to have a positive or negative impact across the board. While this may indicate that architectural design cannot follow simple, universal rules to reach energy efficient results, it on the other hand also suggests that with sufficient case-specific consideration there is remarkable freedom of design. Correspondingly, design guidance and regulations as well as city planning should avoid hard rules on individual properties. To realize the noted freedom of design, energy calculations must be carried out early enough in the design process and throughout it, not just as a separate later step. This calls for close cooperation between architects and energy specialists throughout the building design process to ensure a result that is successful as a whole and in which the various aspects support each other. Another important point regarding case-specific consideration arises from the differences in the impacts of various properties observed between the three studied climates. The current Finnish building regulations at least require that official energy performance calculations are conducted using Helsinki weather data [16]. Based on the results of this study, this can cause a significant discrepancy between the calculated and concrete energy efficiency of a building. For more realistic results, localized weather data should be used instead.

3.3. Applicability and further research topics

The full factorial design of the research allowed a comprehensive evaluation of the chosen variables within the defined context. For wider applicability, several specifics of the study must be considered, as discussed below.

Even between the studied locations, climate had an effect on not only the amount of impact certain design decisions had, but also on whether this impact was positive or negative. Therefore, one should be cautious when applying the results to significantly different climates. At the very least, results regarding heating, cooling and lighting should be considered independently instead of relying on just total energy consumption. On the other hand, the differences between the studied locations greatly increase the geographical coverage of the results. Using the Köppen classification, the studied climates cover most of Northern, Eastern and Central Europe, most of Russia in Asia, and nearly all of Canada [28]. For more immediate context, it should be considered that the simulations were conducted without neighboring buildings or vegetation. These, along with the need for visual comfort or privacy and the resulting use of curtains or blinds, might reduce solar heat gains and natural light especially with low sun angles.

The choice of building type is likely to have an impact on which of the used parameter values would be realistic when applying the results in practice. Many public buildings, for example, may require larger windows or spaces than were studied here. Corresponding to the constants used, different internal heat loads, use schedules, and indoor climate requirements would also affect the resulting heating, cooling, and lighting needs, as would the specific uses for different parts of the space as noted earlier in discussion. Thus, while the results are likely to be rather directly applicable to different kinds of housing, as well as many types of offices, care needs to be taken when considering them in the context of for example schools or hospitals.

Although the simulations were run on a single room, it's important to consider the results in the scale of a whole building. A building in the sample used has on average 53 assisted living apartments, of which 47 are single resident, on 3 above-ground floors. On these floors, apartments comprise on average 54.0% of total floor area. When such a building was simulated using an average spatial distribution from the sample, reference values for properties such as heat loads and ventilation in these, and the defined base case for apartments, the total building energy consumption in Helsinki was 592 947 kWh/a. Correspondingly, using the simulated single room cases for all 53 apartments, combined energy consumption in Helsinki for just the apartments ranges between 72 493–121 295 kWh/a. Taking the above total building figure as the midpoint of the range, the studied design decisions could thus lower or raise the total energy consumption of the building by a notable 8.2%. The comparison is clearly very simplified: in the context of a whole building there would for example be some heat transfer between spaces and a more beneficial ratio of building envelope to floor area, changing the results from those extrapolated from a single room. There would also obviously be windows in the remaining 46.0% of the building, potentially nearly doubling the possible impact. For the other studied climates, the spread between minimum and maximum energy consumption was proportionally close to the above, so the percentual impact would also be very similar, although the difference in absolute energy consumption would be larger.

Several interesting topics for further study were also revealed. First, as even the three Nordic locations in this study had significantly different results, comparisons with a broader climatic scope would be worthwhile. Similarly, a variety of building types with their specific uses could be included. The selection of studied window variables should not be compromised, as although some property may have appeared insignificant here, it might not be under different conditions. Of the variables already included, different kinds of shading including overhangs, curtains, blinds, and combinations thereof could be compared using various schedules and possibly control systems. For increased practical applicability, the comparison should consider both energy efficiency and visual as well as thermal comfort and include at least a selection of window areas, glazing types and solar orientations. As another aspect of practical applicability, comparisons could be performed for new construction as well as renovation regarding energy efficiency, cost, and importantly carbon footprint to possibly find generally recommendable practices or at least act as focused starting points for case-specific evaluation. For a deeper understanding of relative impact, these comparisons could also include other energy efficiency measures, such as amount of wall insulation, and should consider the whole life cycle of the relevant building parts. To avoid unrealistic partial optimization, even studies with a narrow focus must include a sufficient number of related properties.

4. Conclusions

Using a full factorial multivariable simulation study, this research examined the impact of architectural window design has on the energy efficiency of a building through heating, cooling and lighting need, in three climatically different Finnish locations. To account for various design decisions affecting each other, all combinations of the chosen variables were examined. There were some general trends distinguishable between several variables and energy efficiency, most notably: increasing window size on average also increased energy consumption especially in cold conditions, adding fixed shading was only beneficial in cases with especially high cooling need, external shading and glazing g-value could largely be used to compensate each other, and window shape or positioning on the wall had very little direct effect.

Despite general trends existing for the studied variables, it is vital to note that none of these applied across all combinations of other properties. From a design point of view, this indicates that one should be extremely wary of utilizing generalized rules of thumb instead of doing case by case calculations, and especially including such in design guidance, despite the obvious extra effort needed. Correspondingly, it appears energy efficiency does not have to limit architectural expression when these calculations are included. As the impact of a single design decision was and has been found to often be significantly affected by other related decisions as well as local climatic conditions, the energy calculations must be conducted using a reasonably detailed model and localized weather data. Similarly, it became very apparent that in further research on energy efficient windows, even if the main focus is on optimizing a single property, careful attention should be paid to what possibly related variables must be included in at least a limited role to ensure wide applicability and avoid misinterpretation when utilizing the results. The results of this study can be used to inform the selection and to estimate the potential effects of excluded variables. Similarly, the results can aid in the selection of variables for more resource intensive fieldwork in further research. Finally, the literature review revealed clear focus points in existing research on the topic and, conversely, where there is less information available.

Overall, reaching an optimally energy efficient window design in the chosen context was found to be primarily about balancing heating and cooling need, impacts on lighting being relatively minor. Remarkably for the climates studied, cases with considerable cooling need were present in all climates and all solar orientations except north. Although mechanical cooling is currently rare in Finnish residential buildings, this highlights the importance of architectural means in combating overheating especially considering the ongoing climate change.

5. Acknowledgements

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