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THE IMPACT OF DESIGN VARIABLES ON THE HEAT DEMAND OF A RESIDENTIAL BUILDING IN THE COLD REGION

[1]Zahra Alinia, [2]Roya Karimi, [3]Fatemeh Sadeghzadeh, [4]Mehdi Elkaei, *[5]Mehdi mirza Goltabar Roshan

[1,2] PhD student of architecture and member of researchers and elites club, Sari Branch, Islamic Azad University, Sari, Iran.
[3,4]PhD student of Architecture, Sari Department, Islamic Azad University, Sari, Iran
*[*5]Member of the academic staff of the Civil Engineering Department, Sari Branch, Islamic Azad University, Sari, Iran.*

ABSTRACT

This study is about the impact of early design decisions on the heat demand of a small residential building. Heat demand is a significant part of the energy use of residential buildings in the Cold regions. Reducing this demand will reduce the strain on national energy resources and even allow buildings to become energy neutral or independent with the addition of energy supply and storage systems. Based on a case study building of apartments, the simulation study explores the impact of several individual design aspects: insulation, orientation of glass facades and building shape. Furthermore, the balcony facade of the case study building is compared to a plain facade and a sunspace (balconies with a glass facade) in terms of heat demand and comfortable use (operative temperature). Based on these studies a final set of design guidelines is developed for designers interested in designing small residential buildings with low heat demand.

Keywords: heat demand, Cold regions, residential building, Improve energy consumption.

CORRESPONDING AUTHOR

Name: Mehdi Mirza Goltabar Roshan

Affiliation: Department of Dentistry, Prince Sultan Military Medical city, Riyadh, KSA.

INTRODUCTION

Worldwide both governmental and corporate parties have committed to significantly reduce emissions that have been linked to climate changing effects. This generally translates to reducing the use of fossil fuels by switching to sustainable energy sources such as wind and solar, and by reducing energy demand in general. Energy consumption of buildings makes up a significant percentage of total energy demand in the Cold regions. A large part of this is due to heating demand. To meet the energy goals set by international agreements on energy use reduction the EU demands all new buildings to be (nearly) energy neutral by the 31st of December 2020. Because design changes are costly, it is preferable that designers are aware of the impact their design decisions can have on heat demand. By taking this into account in an early stage of the design development, mistakes can be avoided that would require an investment of time and money to correct.

A study of global scholars found that the way residential areas are planned and the form of their layout play an important role in combating global climate change and reducing building energy consumption. Hanna et al. demonstrated the influence of the layout form of residential buildings on building energy consumption [1]; C. Ratti et al. demonstrated the influence of residential zoning on residential energy consumption up to 10% in 2 cities, Toulouse and Berlin [2]; Okeil explored the relationship between building spacing and energy consumption at the block scale level based on the influence of daylight radiation on building energy consumption [3]. Caroline explored the relationship between the morphology, block density, and base layout factors of two-story detached houses and the daylight heat gain and heating energy consumption of buildings [4]; Ayşegül explored the relationship between the morphological layout of buildings and the overall energy consumption of buildings based on the influence of daylight radiation, pointing out that the simulation of building energy consumption at the urban scale is difficult due to the interference of building shadows, and related research needs to be strengthened. [5] The planning factors of building clusters (density, floor area ratio, height, etc.) have been shown to change the energy consumption of buildings by altering the site microclimate [6]. Therefore, building energy consumption can be reduced if appropriate changes are made to the planning factors of a residential area [7], [8]

As in any study a research question has been formulated that describes a specific lack of knowledge and the desired final product. In this case the lack of knowledge is the specific impact of design decisions on the heat demand of a residential building in the Cold regions. What is the impact of early design decisions on the heat demand of a residential building in the Cold regions and what heat demand reduction guidelines can be established for designers?

Heat Demand in Residential Buildings

Occupant Comfort and Health

It is commonly accepted that comfort and health of building occupants demands a stable temperature roughly in between 18 and 26 degrees Celsius. In this study the heating set point, the temperature below which the heating will be turned on, will be set at 19 degrees Celsius and the cooling set point at 26.

The specific preferred comfort temperature differs per gender, age, personal health and personal desire so it is hard to be more specific unless the specific users and their personal desires are known. In case of an elderly home for example a higher minimum temperature like 21 degrees could be assumed and cooling is more important due to the risks posed by fragile health during heat waves.

Climate Conditions in the Cold Regions

The outside temperature in the Cold regions often goes well below the minimum of 18 and therefore heating is a common requirement for residential buildings. The days that the outdoor temperature goes above 26 degrees in the Cold regions are limited and therefore cooling systems in residential buildings are a rare sight. High solar gains can cause overheating and therefore sun shading and natural ventilation are often applied as methods to keep indoor temperatures from rising above comfort levels.

Modeling the Case Study Building

Energy Modeling Software

To calculate the heat or cold demand of a building for a whole year based on weather data for every hour of the year a dynamic energy simulation has to be performed. Therefore, it has become common practice to use energy modeling software to run these calculations. A lot of this software is based on Energy Plus. Energy Plus is energy modeling software developed by the U.S. Department of Energy first released in 1998 [9]. It is used to model the energy consumption for all temperature and electricity related systems. The heat simulations are based on heat balance theory and include the dynamic effects of thermal mass.

Based on the goals of this study and academic requirements the criteria for software tool selection were:

- The tool should be easy enough to learn to use within the scope of this study.
- The tool should be able to give detailed results including heat demand and operative temperature on an hourly basis per zone.

Software Choice

Based on the criteria above several programs were considered for use:

- TRNSYS
- Design Builder
- Honeybee (a Grasshopper plug-in)

TRNSYS (Transient system simulation tool) is commonly used for many energy related simulations due to its capabilities for simulating complex systems. The input for TRNSYS is purely numerical and lacks a geometry modeling interface. Instead it focuses more on systems and databases. It has recently added a plug-in for Google Sketch up (TRNSYS3D) to allow users to import their models from Sketch up into TRNSYS.

Design Builder is an input interface for Energy Plus that allows for modeling and assigning values in a 3D environment. Its software specifically developed for engineers and architects.
Honeybee is a plug-in for grasshopper. Geometry input is modeled in Rhino modeling software and then connected to calculation modules in Grasshopper, which is a graphical interface for programming connected to Rhino geometry that is most commonly used for parametric design. The Honeybee plug-in provides specialized calculation modules for thermal energy related simulations. Honeybee has free and publicly available tutorials provided by one of the plug-in developers from MIT, Chris Mackey. This makes getting started with the software more appealing. After comparing these three options TRNSYS was dismissed because it is unnecessarily complex for the relatively simple simulations of this study. So, the choice came down to either Design Builder or Honeybee which were comparable in many ways.

Honeybee was eventually chosen over Design Builder for three reasons: Firstly because of its promising results in a study by fellow student, Anne Leeuw, on energy producing high rise facades [10]; secondly because of the tutorials that are so easily available for it; and finally, because of the transparency and flexibility of its calculation

Case Study Building Description

The building that will be re-designed based on the findings of this study is a small residential building built. It has with the three top floors being identical and the bottom floor slightly differing due to the space required for entrance, storage and utilities. One facade is almost completely glazed (roughly 80%) and has balconies, the other facades have identical windows with sliding panes. The facade opposite the balconies has roughly 20% glazing and the side facades roughly 10%

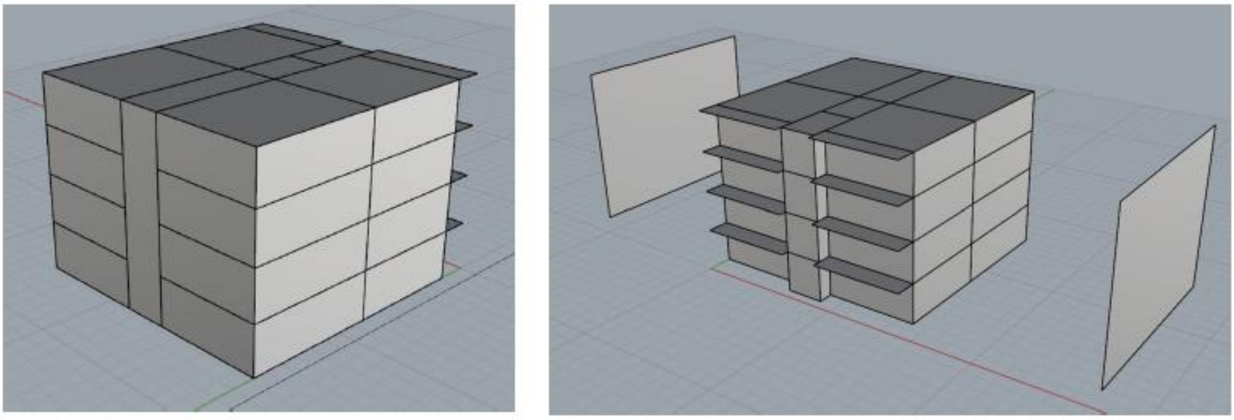


Figure 1 The case building: photos of the facades the rhino model

Impact Studies

Plain Facade: Insulation

Case Description

The geometry used in the simulations is a simplified version of the case study building. Each floor is divided into four equal zones. This dramatically reduces the simulation times and still suffices for the purpose of this study, which is to show the general impact of individual design decisions.
In this particular study the facades are identical and consist of 20% glazing. The rest of the facade consists of a basic buildup of limestone blocks and insulation material.

Variables

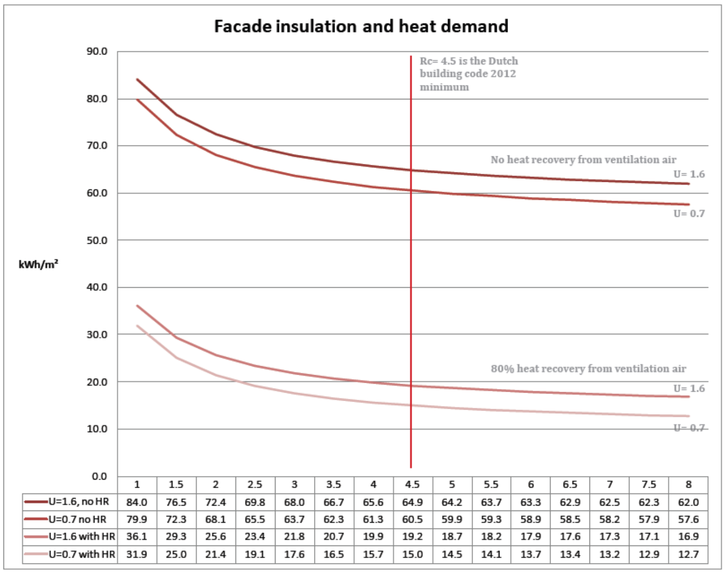
Main variable is the insulation value of the opaque facade surface. Several sets are simulated for different values of window U value (1.6 or 0.7) and Heat Recovery (none or 80%).

Discussion

Simulations of the building with an increase in value for insulation of the facade show a decrease in impact as the insulation level rises. The greatest impact, measured in drop in annual heat demand, is from a Rc value of 1 to about 2.5 after that the impact gradually levels off. The heat demand reduction from Rc=1 to Rc= 4.5 ranges from 25% to 50% for the different variants. But the impact of increasing Rc from 4.5 to 8 barely reaches a decrease of 10% in annual heat demand.
It is also important to note the immensely significant impact of heat recovery when you have a well-ventilated building. Heat demand for a building with Rc value of 4.5 and heat recovery of 80% is well under 30% that of the heat demand of the same building without heat recovery.

Conclusions

The impact of insulation decreases as the Rc value rises. The difference between an Rc of 1 and 2.5 is very significant. But an increase from 4.5 to 8 has much less impact. Insulation is important but only up to a point. The building code minimum of 4.5 is already quite decent. In a standard concrete facade with an average performing insulation material (0.03 W/m-K) on the outside this can already be achieved with an insulation layer of 125 mm thickness.



	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
U=1.6, no HR	84.0	76.5	72.4	69.8	68.0	66.7	65.6	64.9	64.2	63.7	63.3	62.9	62.5	62.3	62.0
U=0.7 no HR	79.9	72.3	68.1	65.5	63.7	62.3	61.3	60.5	59.9	59.3	58.9	58.5	58.2	57.9	57.6
U=1.6 with HR	36.1	29.3	25.6	23.4	21.8	20.7	19.9	19.2	18.7	18.2	17.9	17.6	17.3	17.1	16.9
U=0.7 with HR	31.9	25.0	21.4	19.1	17.6	16.5	15.7	15.0	14.5	14.1	13.7	13.4	13.2	12.9	12.7

Figure 2 Heat demand (in kWh per m2) of the middle floor of the study building at different levels of facade insulation

Plain Facade: Orientation

Case description

The simulated building is similar to the one in 6.2 except for one façade now having 80% glazing.

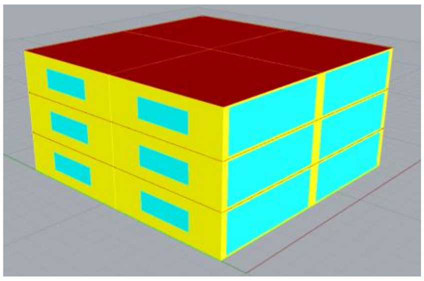


Figure 3 A visualization for the geometry with glazing for study 2 with the 80% glazed facade on the right.

Discussion

The direction the 80% glazed part of the building faces significantly impacts the heat demand of the building. With heat recovery this building can easily meet the maximum heat demand set for a passive house (15kWh/m2) at the right orientation.

With glass that has a U value of 1.6 the facade only performs better when close to facing directly south. A well-insulated version (U= 0.7) performs better even when facing east or west and has a 30% heat demand reduction potential when facing straight south.

Conclusions

Solar heat can play a significant role in reducing heat demand in a building that is well insulated. Any facade with a roughly southern orientation in between SW and SE can benefit from this. It is however important to note that overheating is taken into account when designing glass facades. Measures against overheating include sunshading in summer and enabling ample natural ventilation during times of excessive heat gain.

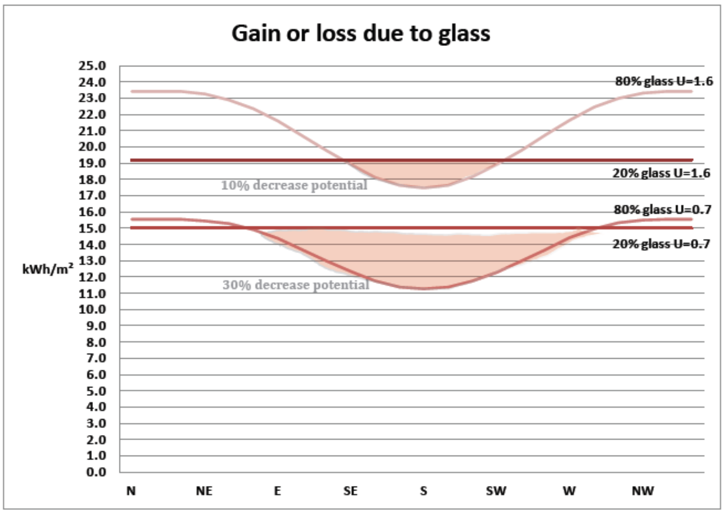


Figure 4 Heat demand comparison between a 80% and 20% glass version showing the potential heat demand reduction for different orientations. Note that glass facades will lose more heat than they gain when they aren't orientated towards the south. The lines for the 20% glass facade represent the value of the previous study and not of a version that was simulated for different orientations.

Plain Facade: Building Shape

Case Description

This case includes two different geometries: the geometry of the previous studies, shape A, and an adjusted geometry that has all zones arranged in a line from west to east, shape B.

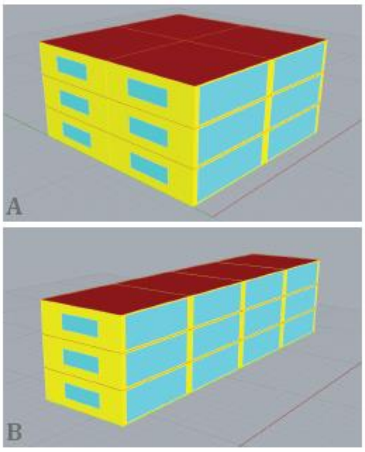


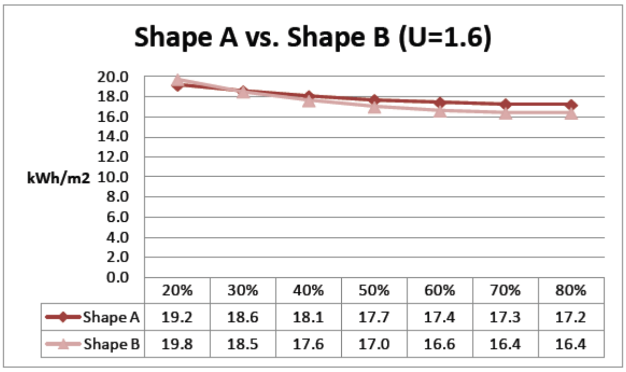
Figure 5 Honeybee visualization of compact shape A (top) and 'sun surface' shape B (bottom).

Both glass facades face south in this study to show the maximum potential.

Conclusion

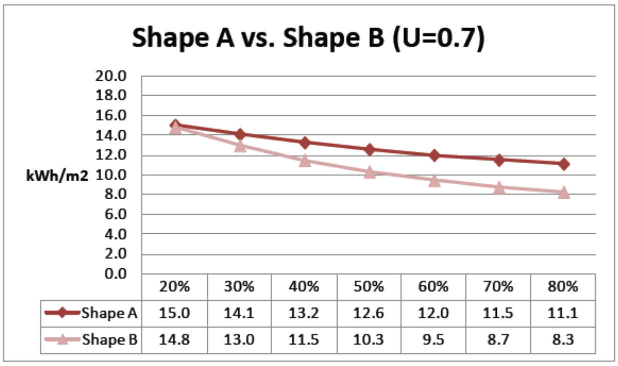
With high insulation values version A has a higher heat demand than version B even at 20% glass surface and it only gets worse from there. Version B has a steeper increase in cooling load as the glass percentage rises.

A downside of glass facades is that they can easily lead to overheating of a building. Operative temperature for zone 2A (western side zone on middle floor) shows that this is the case for the study building for a majority of the year.
With a high insulation value, making use of solar heat by increasing the surface area of the building facing the south is very advantageous in terms of reducing heating demand.



	20%	30%	40%	50%	60%	70%	80%
Shape A	19.2	18.6	18.1	17.7	17.4	17.3	17.2
Shape B	19.8	18.5	17.6	17.0	16.6	16.4	16.4

Figure 6 Heating demand and cooling demand for version A and version B. Glass percentage of the south facade varies from 20% to 80%.



	20%	30%	40%	50%	60%	70%	80%
Shape A	15.0	14.1	13.2	12.6	12.0	11.5	11.1
Shape B	14.8	13.0	11.5	10.3	9.5	8.7	8.3

Figure 7 Heating demand and cooling demand for version A and version B. Glass percentage of the south facade varies from 20% to 80%

Sunspace: Insulation

Case Description

The main geometry remains the same as the first study building, but now it has added sunspace volumes on the south facade. These volumes have a glass facade facing the exterior as well as on the interior side.

Variables

Two sets are simulated: one with an interior window U value of 1.6 and one with 0.7. In both sets the exterior window goes through the U values of 5.8, 3.8, 1.6, and 0.7. These values approximate the insulation values of respectively a single pane window, a (simple) double pane window, a window meeting building code minimum standards and an extreme high-performance window. It should be noted that the value of 0.7 is that of the glass itself and that in such high-performance windows it is often the window frame that is less insulating and therefore causes more heat loss than can be expected when only taking the 0.7 U values into account.

Discussion

The results show that lowering the U value of the outer facade decreases heat demand (See Figure 43). Heat demand goes down for both the set with an interior window with U= 1.6 as well as for the one with U= 0.7.

What is interesting is that with an interior window with U= 1.6 the decline is steeper and although it starts out with a higher heat demand at U= 5.8 for the outer window, it ends up with a lower heat demand at U= 0.7 for the outer window compared to the version with an interior U= 0.7. These results are for a middle floor so heat loss through floor and ceiling are significantly reduced.

Conclusions

Based on these results it could be argued that reducing heat demand with a sunspace is best achieved with a very low U value (below 1.6) for the exterior window. At the same time, it is not advisable to invest in a lower U value for the interior facade compared to that of the exterior window since this seems to work counterproductively. This result makes sense since U value is an indicator of heat flow and in this case we want heat to flow from the sunspace into the interior space more rapidly than it flows to the outside.

So a relatively lower U value on the interior side seems advisable when the exterior side is well insulated (U= 1.6 or below). This only applies if the sunspace is kept relatively airtight so there is no significant heat loss due to air flow.

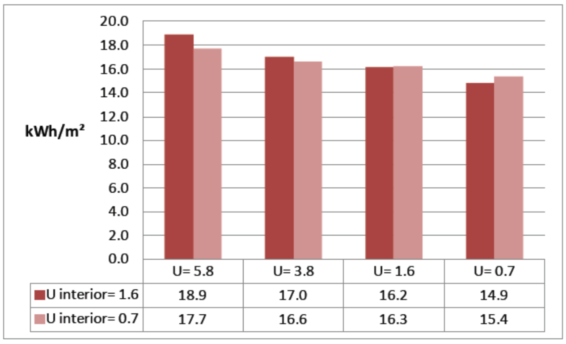


Figure 8 Heat demand for the study building with a Sunspace. Two different U values of glass for the thermal skin are set against a variation of U values for the glass of the exterior facade of the Sunspace.

Sunspace: Building Shape

Case Description

Since the number of zones with a south facade is doubled in shape B, the number of sunspaces is also doubled.

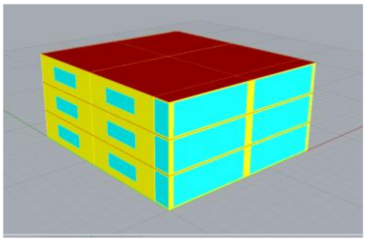


Figure 9 Visualization of shape A with sunspaces.

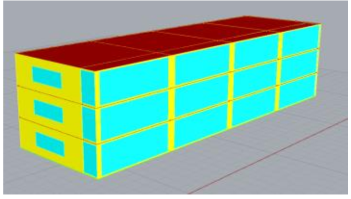


Figure 10 Visualization of shape B with sunspaces.

Variables

For both shapes A and B two sets are run for window U= 1.6 and window U= 0.7. In these sets the percentage of glass on the interior side of the sunspace is varied from 20% to 80%.

Discussion

The results (see Figure 50 and Figure 51) again show that the elongated shape (B) performs better in terms of heat demand especially if the U value for the exterior windows is low (U= 0.7).
Higher percentage of glass translates to lower heat demand in all sets.

Conclusions

The percentage of glass on the interior side of the sunspace directly relates to the heat demand. A higher percentage of glass leads to lower heat demand. This was expected since more glass means both more direct sunlight entry and more heat transmittance through the interior facade.

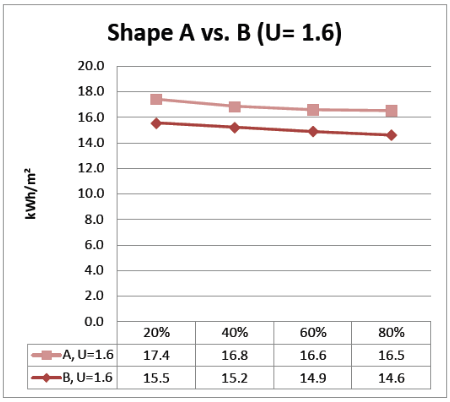


Figure 11 Graph showing heat demand for shape A and B buildings with sunspaces for varying percentage of glass on interior side of sunspace.

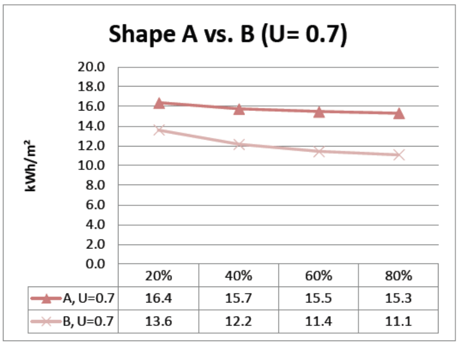


Figure 12 Graph showing heat demand for shape A and B buildings with sunspaces for varying percentage of glass on interior side of sunspace.

Design Guidelines

Introduction & Application

These guidelines are the answer to the main research question formulated for this study: What is the impact of early design decisions on the heat demand of a residential building in the Cold region and what heat demand reduction guidelines can be established for designers?

The guidelines are based on the results from a range of studies into the impact of several design variables on the heat demand of a representative study building. These results were gained by simulating the study building in Energy Plus related software and should be seen as only generally representative of the situation in a Dutch (or similar) climate setting. To make the information gained from the studies more insightful to designers an attempt was made at translating a technical story into a design story.

These guidelines are intended for designers that want to design residential buildings in the Cold regions with low heat demand. They do not give specific instructions on how to design a building. Instead, they give an idea of what design variables have a strong impact on heat demand and which ones should be prioritized.

Guidelines per aspect

Insulation

In the Cold region facade insulation needs to be at a minimum Rc value of 4.5 already due to building code requirements. As shown in figure 31, the impact of increasing insulation above 4.5 is limited.

Increasing window insulation beyond the building code requirement of U=1.6 is definitely worth it when making use of large glass surfaces for solar heat gain. Looking at Figure 11 and Figure 35 it becomes clear that both the literature and this study support the application of well insulated glass as it increases solar heat gain potential.

Orientation of Glazed Facade

Apart from this study confirming the effectiveness of well insulated glass this study also supports the use of glazed facades for solar heat gain. The results from this study show that favourable results with well insulated glass can even be achieved beyond the range as described in the literature. The optimum is still confined to the purely south facing facade.

Building Shape

The impact studies clearly show the potential of decreased compactness in favor of a south favoring shape factor with a longer facade facing south. Since the advantage here is in solar heat gain a high glass percentage in this facade and an improved insulation value (below U=1.6) are crucial.

Sunspaces

In a static model as used in this study the heat demand reduction potential of a sunspace is not necessarily better than of a plain facade with the same glass percentage. In a flexible model it is likely to perform better though and it is definitely a better alternative to a balcony in both heat demand reduction potential and in offering a comfortable use zone even in winter (on sunny days).

General Discussion and Conclusions

The many factors involved in heat demand and building design make it a complicated subject. In this series of impact studies an attempt was made to simplify things by focusing on a limited set of design aspects (insulation, orientation of glazed facade, building shape). By including the façade aspects of the case study building (glazed façade with balconies) and variations on it, an attempt was made to make the link between the studies and the case study building more clear.
Heat balance is complicated and a lot of factors are involved. This study is only showing the heat potential in limited scenarios. In reality (among other things) the user is an added factor that can seriously impact the actual heat demand in many ways. They might want a higher heating set point, they might open windows for fresh air on cold days, and they might open the sunspace zone to the interior zone at appropriate or inappropriate moments. It cannot be emphasized enough that this study simply shows the potential benefit to heat demand of certain design aspects. In an actual design these benefits might not translate 1 to 1, and serious consideration of the behavior of the user would be necessary.

Initial results on sunspaces were conflicting, with an early test study showing reduced heat demand when a sunspace was added and then the first impact study showing differently. Although the shapes A studies show some ambiguity as to the advantage to heat demand reduction as compared to a plain facade, the shape B studies show a much clearer image. Sunspaces basically combine the advantages of both the plain facade (maximum heat capture) and the balcony (shading during summer). Although it is not investigated in this simulation study, it seems reasonable that this performance would only improve by occupants making proper use of the flexibility of the sunspace. Opening it to the interior to allow heat in during sunny cold days and opening it to the exterior to lose heat on warmer days.

CONCLUSION

1. Facade insulation (of opaque parts) is only part of the solution. The building code minimum of Rc= 4.5 is already quite decent and an improvement to Rc= 8 is only a minor improvement.
2. Orientation is an important aspect of employing solar heat gain to reduce heat demand. Southern orientations have significant heat demand reduction potential that can result in annual heat demand reduction even with the building code max. value of U= 1.6 for the windows.
3. Building shape isn’t just about compactness. With modern well insulated buildings creating sun surface to increase solar heat gain can significantly reduce heat demand, well outweighing the slightly increased transmission losses.
4. Sunspaces are an improvement on the balconies (as defined in this study) in two ways in terms of heat demand: they allow more use of solar heat gain and reduce heat loss due to creating a buffer zone.
5. Sunspaces also allow for comfortable midday to evening use during sunny cold days.
6. in all studies the importance of well insulated windows (U= 0.7) became evident. They allow for maximizing use of solar heat gain whilst limiting heat loss through transmission.

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