# Reducing Space Heating in Office Buildings Through Shelter Trees

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## Abstract

Although the sheltering effects of vegetation have been known, there is lack of quantitative studies on reducing wind speed and thereafter space heating in Scotland and even in the UK. This paper reports the development of a computer model that simulates the effects of shelter trees on space heating of a building. It also presents a quantitative study where the model was applied to simulate thermal performance of a typical cellular office in Scotland with and without protection of trees from wind which is significantly stronger and sunny hours are less in the winter in the areas than elsewhere. A statistical weather analysis was carried out to ensure the shelter vegetation was planted at upstream direction of the prevailing wind of the heating season at the location to provide best sheltering protection. The study predicted 4.45% annual heating energy savings for a typical office building in Scotland, an equivalent a reduction of in 400 kg/floor area on $CO_2$ emissions if natural gas was the heating fuel. This study also suggests that the benefit would be more significant in buildings with curtain walls of which U-value is much lower than a standard wall and in residential buildings as the wind was predicted stronger during the night time in the region.

# 1 Introduction

The effects of trees, such as shelterbelts, hedges and woodlands have been known on reducing wind speed and thereafter space heating for many decades. Suffered from strong wind in winter, many Scottish cities, such as Edinburgh benefit from well planned and planted trees for their shelter and ameliorative effect on wind flows and local climate. The effects of trees, such as hedges, shelterbelts and woodlands have been well known on reducing space heating for many decades. Much research has been done on various aspects of this issue. A comprehensive survey confirms that this reduction will be more significant in windy places [1].

Due to the nature of turbulent boundary layer flow, wind effects on shelter tress and consequently on space heating in buildings are complex and individual. They are subject to many factors, such as local climate, topography, landscape, shelter vegetation, the building and its surroundings. And these will consequently affect the reduction on heating energy consumption, this has been confirmed by Heisler and his colleagues in a series of studies [2-5]. Although there have been many studies carried out investigating the shelter and ameliorative effect on heat losses in buildings, the evident is that the results span over a wide range which gives only qualitative information if not confusing. For instance the prediction of reduction of annual energy saving to shelter trees varies from 3% to 50%, and for infiltration only there is a huge discrepancy in predicted reduction[1]. Obviously such variation is due to local topography, surrounding terrain, physical characteristics of the shelterbelt, building geometry, and the relative location of surrounding buildings. They all influence the mechanism of heat dissipation from any specific building. The research in UK was carried out in 50's and the results were actually rather qualitative [6]. The most recent investigation conducted in Milton Keynes was quantitative. But only speed reduction and solar access were measured, heating in buildings was excluded in this study [7].

Moreover, many of the studies were actually on the reduction on wind speed and then on infiltration[8]. This uncontrollable infiltration, although important, is only one part of the total heat losses from a building. Dissipation via the external surfaces of a building envelope accounts about half of the total heat losses and this portion is even higher for new buildings which are normally more airtight and with large glazed areas. No much research, however, has been found on the shelter effect on the surface heat exchange of building envelope. This might be due the facts that surface heat exchange is extremely complex and measurement in either field or laboratory is difficult. The shelter effect on reduction of heating energy would be incomplete without studies on convection heat dissipation on the external surfaces of a building.

This study was an attempt to develop a computer model to simulate thermal performance of a building under various wind conditions. The model should be sensible enough to response the changes of the wind speed due to the presence of a windbreak in windward direction.

# 2 The Methods

The methodology applied in this quantitative study comprised of three parts, statistical analysis of local weather data, wind reduction prediction and thermal dynamic modelling of a representative building. A dynamic thermal performance package, TAS was used to assess the impact of shelterbelts on the energy consumption of space heating in office buildings[9].

## 2.1. The Weather Features

The statistical analysis was carried out using the facility of report generator in TAS. Rewriting the scripts with various "filters" allows the some weather features to be counted, such as the wind speed and wind directions, solar radiation and cloud cover. One of the major tasks of this statistical analysis was to find the direction of the prevailing wind during the heating season, so that the windbreak could be planted to this direction for a maxim protection.

## 2.2. The Physical Background

Heat losses through a building are mainly in two ways: air infiltration and heat conduction through the building fabric.

### Air infiltration

Air infiltration is the passage of air into a structure through joints, pores, cracks, and other openings. Such flows result from pressure differences between inside and outside air, which is mainly caused by the force of the wind. The mass flow rate of air infiltration is expressed as follows:

$$m = 0.62(2\rho)^{1/2} fA|\Delta p|^{1/2} \tag{2-2-1}$$

where m=mass flow rate of air infiltration, kg/s
ρ = the air density on the inlet side of the aperture, kg/m$^3$
fA= the area of the aperture, m$^2$
Δp=the pressure drop across the aperture, Pa

The heating load due to the air infiltration is:

$$Q_i = 0.62(2\rho)^{1/2} fA|\Delta p|^{1/2} C_p (T_{ao} - T_{ai}) \tag{2-2-2}$$

where $C_p$=the specific heat capacity of air at constant pressure, J/kg K
$T_{ao}$=the outside air temperature, K
$T_{ai}$ =the inside air temperature, K

In addition, the wind pressure on an aperture is assumed to be:

$$p_w = \frac{F_s c_w \rho v(h_b)^2}{2} \tag{2-2-3}$$

where $p_w$=the wind pressure, Pa,
$c_w$= the wind pressure coefficient,
$v(h_b)$ =the wind speed at the building reference height $h_b$, m/s,
$F_s$= the adjustment factor applied to certain apertures.

### Dissipation

The heat losses due to conduction through the building fabric are dependent on the thermal transmittance, areas of the fabric and the difference in temperature between the outside and the inside air. The effect of the wind on influencing this heat dissipation is limited to the external surface heat transmission. The external surface heat flow can be written as follows:

$$Q_{ext} = A(h_c + h_r)(T_{ao} - T_{ext}) \tag{2-2-4}$$

where $Q_{ext}$=external surface heat flow, Watt,
A = external surface area, m$^2$,
$h_c$ = external convective coefficient, W/m$^2$K,
$h_r$ = radiative heat transfer coefficient, W/m$^2$K,
$T_{ext}$ = the external surface temperature, K.

According to CIBSE Guide [10], the external convective coefficient is defined as:

$$h_c = 5.8 + 4.1V \tag{2-2-5}$$

where V is the windspeed. The windspeeds at roof surfaces are taken as 1.0, 3.0 and 9.0m/s corresponding to sheltered, normal and severe exposures [10], and 2/3 of these values are assumed for wall surfaces. The definition of the windspeed is vague. No precise definition of 'at roof surfaces' is given, even though there must be some height above the roof surfaces associated with the windspeed since the windspeed at the surface itself is zero. The same problem occurs for wall surface windspeeds. Therefore, there is a need for further research aimed at standardising the position on or around a building at which surface windspeed should be recorded for use in clarifying the CIBSE definition.

The radiative heat transfer coefficient may be expressed by the following equation:

$$h_r = \frac{\sigma\left(T_{ext}^2 + T_{env}^2\right)\left(T_{ext} + T_{env}\right)}{1/\varepsilon_{ext} + \left(A_{ext}/A_{env}\right)\left(1/\varepsilon_{env} - 1\right)} \tag{2-2-6}$$

where:
$\sigma$ = Stefan-Boltzmann constant = 5.669 x 10$^{-8}$ W/m$^2$K
$T_{env}$ = temperature of surrounding environment (°C)

$\varepsilon_{ext}$ = emissivity of the external surface
$\varepsilon_{env}$ = emissivity of the surrounding environment
$A_{ext}$ = surface area of the external element ($m^2$)
$A_{env}$ = relative area of the radiating environment ($m^2$)

It seems that the radiative heat transfer coefficient is not affected by the windspeed, but is influenced by the temperature. In fact, the surface transmission due to radiation is affected by windspeed. The higher the wind speed, the lower the absolute temperatures of the external surfaces, thereby reducing the rate of radiation heat transfer.

## 2.3. Wind Speed Reduction of Shelter Trees

It is difficult to specify the types of trees of a shelterbelt and to quantify accurately its effects on wind. Hence it was decided to combine findings of a literature survey and the results of a CFD modelling carried out in the School. There following assumptions were make, the shelterbelt was a straight windbreak with a height of 18m and length of 120m, both of which were three times of those of a building located downwind within a distance of 54m, three times of the height trees. Its had a medium porocity (optical porocity: about 30%) in winter [11]. Supported by the literature review, the CFD modelling calculated respectively a wind reduction of the windbreak in the leeward area about 50% for the prevailing wind, 35% for 15° asides of the direction and 15% for 45°. Zero reduction was assumed for all other wind directions [12].

It was assumed that the shelterbelt was planted to the Southwest of the building to gain the maxim sheltering protection. Furthermore the building in the leeward of a shelterbelt experienced the wind conditions as it had been in an open space with reduced wind speeds, and the reduction rate were direction dependent as mentioned above. Throughout the whole heating seasons (≈3624 hrs)., the hourly wind speed values in the weather file for Edinburgh were individually adjusted to reflect these changes in the wind speed parameter. Running TAS with the original weather file and the modified file would produce two performances: one with not shelter protection and the other taking into account of the sheltering effect.

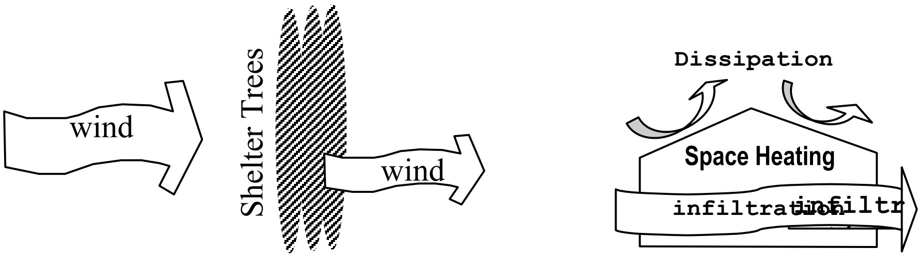

**Figure 1 Schematic diagram of sheltering effect of trees on space heating**

## 2.4. The Sensitivity Test

Using a single space of rectangular model building model, a sensitivity test was conducted to explore how a building could be correctly built with TAS that its thermal performance would response adequately to the changes of wind speed. That included examined the effects on the surface heat convection and infiltration due to the change in wind speed. This model was a single zone building of $5 \times 4 \times 3m^3$ with two double glazing windows on its East and West facades, and each had area of $2.0m^2$. Of these windows a small percentage of opening area was made to allow 0.5 ACH at wind speed of 3.0m/s. The U-values of the ground floor, roof, walls and windows were 0.29, 0.27, 0.26 and 2.6 $W/m^2K$ respectively. The examined variables, were the infiltration rate, temperature of the external surfaces, heat loses on the building envelope. A special weather file was prepared for this test, where for a consecutive ten-day period the ambient temperature was fixed to 5C, relative humility; 60%, cloud cover; 1, and wind direction; South. The global radiation was made zero to minimise the account of radiation heat exchange at the surfaces. In four test runs, the wind speed was set to 1.0, 3.0, 5.0 and 10m/s respectively.

## 2.5. The Model Building

A recent survey conducted on some 3400 non-domestic addresses within the UK indicates that about 88% of office buildings are characterised as 'cellular' office space. In addition, about 1/3 of these cellular offices are of four storeys in height, with a layout of 'side-lit strips'[13]. It appears that a large percentage of the existing small office buildings in Scotland are housed in renovated residential accommodations or flats normally about two to three storeys in height. The percentage of flats in Scotland (41% of the housing stock) is significantly higher than in rest of the UK [14]. The building in this study was therefore modelled as a simple two-storey small office building in the category of 'Type 1' office buildings bearing features like cellular side-lit rooms, naturally ventilated, small floor area (100~3000$m^2$), and usually constructed in converted residential buildings[15].

Office occupancy pattern was considered: 0800 to 1800, Monday to Friday. The heating period was accounted from November to March, when all rooms in the office were maintained at 18°C throughout the heating season during the occupied period.

Figure 2 The model office building

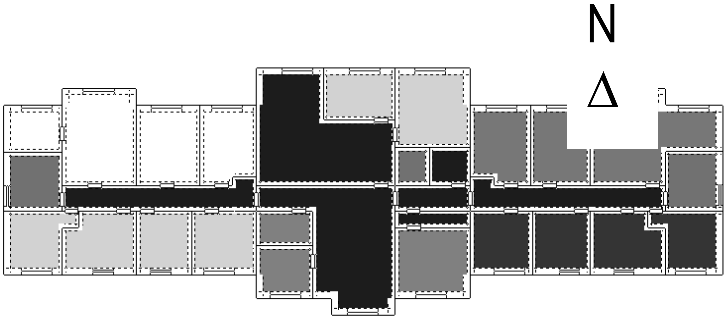

**Figure 3 Zones on the ground floor**

All thermal properties of the building were similar to those in the test case, including the U-values of external walls, roofs and windows. Like the test case, the infiltration rate of the model building was set to 0.5 $ACH^{-1}$, by tuning the opening areas of all apertures on the external walls to achieve the given rate at an external wind speed of 3 m/s. The air infiltration of the building would be then responsive to changes of wind speed in wind data in simulation. More details regarding to this TAS model can be found in reference[15]

# 3 Results

## 3.1 Wind Conditions

As the results of the weather analysis, the Southwest wind was revealed as the prevailing wind in Edinburgh from 0800 to 1800 during the heating season, although the wind from North also appeared to be rather significant. (Fig 4) The vegetation windbreak was then located to the Southwest of the building to gain the maximum sheltering benefit.

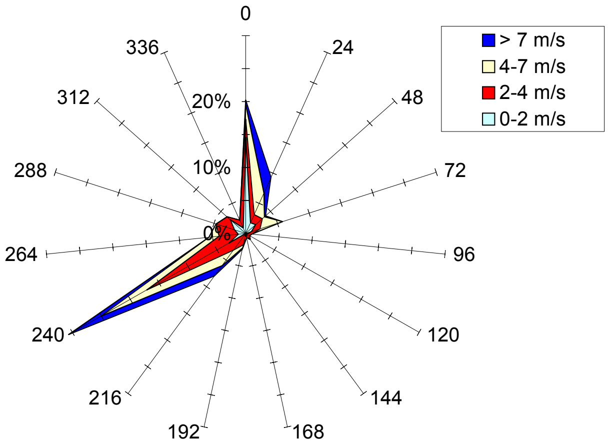

**Figure 4 the wind speed and direction for Edinburgh (from November to March, 8:00 to 18:00, Monday - Friday) when ambient outdoor air temperature is below 5 °C**

## 3.2 The Sensitivity Test

As expected the average temperature of external surfaces of the building varied with the wind speed, particularly at the windows surfaces, which reduced over 6% when wind speed increased from 1m/s to 3m/s. It reduced over 15% when wind speed changed from 1 to 10 m/s (Fig 5).

**Figure 5 average temperatures at the external surfaces of the simple test building Vs wind speed**

As the equation that calculates heat exchange coefficient at the external surfaces in TAS accounts the wind speed in the weather file as the flow speed, the coefficient had the same value for all surfaces. Therefore the surface temperature did not change from one orientation to the others, which is incorrect. Such approximation appears to be acceptable in modelling studies for general purposes in practice. But for the research point of view it appears insufficient. How it can be modified to be dependent of wind incidence and wall orientation would be an interesting research topic.

Table 1 lists the heat loses and the surface temperature at the building envelope. Clearly the infiltration heat lose was very sensitive to the change in wind speed. There was a rapid increase, nearly 240%, when the wind increased its speed from 1.0 to 3.0 m/s. This part of heat loss was linearly proportional to the wind speed, as its value doubled when wind speed rose from 5.0 to 10.0 m/s. As wind became stronger, the heat loss by the conduction through the building envelope increased too, although very little.

The table reveals further that the increments in the heat loss on the walls and roof are much less significant than that of windows. When the wind increased its speed from 1 to 5m/s, the rise in heat loss via the windows was 6.6%, whilst there was no significant increase on heat loss on the walls and roof. As the U-value of the windows are much higher than that of a wall, the external convection has more weight in the overall thermal transmittance. The wind induced increase on surface heat exchange would consequently lead to a remarkable change in heat loss through this part of building envelope. This simple modelling exercise proves that higher the U-value, the more significant the increase on heat on this part.

| Wind Speed | Heat Losses | | | | | Surface Temperature | |
|---|---|---|---|---|---|---|---|
| | Infiltration (kWh) | Walls & roof | | Windows | | | |
| | | KWh | Wh/m$^2$ | kWh | Wh/m$^2$ | Opaque | Glazing |
| 1 m/s | 0.7 | 1.4 | 21.8 | 2.3 | 572.5 | 5.2 | 6.5 |
| 3 m/s | 2.5 | 1.3 | 21.6 | 2.4 | 597.5 | 5.1 | 6.1 |
| (from 1 to 3 m/s) | 237% | -1% | -1% | 4% | 4% | -2% | -6% |
| 5 m/s | 4.3 | 1.3 | 21.6 | 2.4 | 610 | 5.1 | 5.8 |
| (from 3 to 5 m/s) | 73% | 0 | 0 | 2% | 2% | 0 | -5% |
| 10 m/s | 8.5 | 1.3 | 21.6 | 2.5 | 623 | 5.1 | 5.5 |
| (from 5 to 10 m/s) | 101% | 0 | 0 | 2% | 2% | 0 | -5% |

**Table 1 The simple test building in various wind speed**

Furthermore the heat loss through the windows was almost twice as much as that through the walls in this case where windows areas were not remarkably large, less than 7% of all external wall area. Its heat loss per surface area was over 26 times of that on the walls during a calm day, and increased to almost 30 times when wind was strong. This suggests that for a building with large glazing areas, the wind effect on increase the total heat losses for a whole building would be much more significant. Wind sheltering effect on space heating would be more evident for offices with full height glazing facade or curtain walls.

## 3.3 Total Energy Consumption over the Heating Season

Table 2 reveals an energy savings of 4.45% (or 2100 kWh) in whole building for the sheltered condition when compared to the unsheltered condition during the heating season. This overall energy demand for both simulations may be further broken down to view the losses from individual rooms due to conduction, convection and infiltration. The western offices typically had a higher heating energy load for both sheltered and unsheltered conditions, which was due to the exposure to the prevailing wind from Southwest.

| | | | Heating Load (MWh) | | |
|---|---|---|---|---|---|
| | Zone Name | Zone No | Unsheltered | Sheltered | saving |
| | Stairwell and Lift | 1 | 2.87 | 2.50 | 12.7% |
| | Communal Area | 6 | 9.46 | 8.45 | 10.7% |
| | Offices: | | | | |
| Ground floor | SE | 2 | 2.73 | 2.68 | 1.9% |
| | NE | 3 | 3.72 | 3.66 | 1.8% |
| | Central S | 4 | 1.73 | 1.70 | 2.1% |
| | Central N | 5 | 1.97 | 1.93 | 1.9% |
| | SW | 7 | 2.75 | 2.69 | 2.0% |
| | NW | 8 | 3.81 | 3.73 | 1.9% |
| First floor | NE | 9 | 3.30 | 3.32 | -0.6% |
| | SE | 10 | 3.69 | 3.52 | 4.6% |
| | Central S | 11 | 2.32 | 2.22 | 4.6% |
| | Central N | 12 | 1.77 | 1.77 | -0.3% |
| | SW | 13 | 3.71 | 3.54 | 4.6% |
| | NW | 14 | 3.37 | 3.39 | -0.5% |
| | | Total | 47.19 | 45.10 | 4.5% |

**Table 2 Comparison of the heating loads in each zone in the building over the heating season**

The top floor had a large external surfaces for heat dissipation, hence it would benefit more from the sheltering windbreak. The heating energy saving was 2.2% for the top floor due to the sheltering effect and the figure was only 1.9% for the offices on ground floor.

Very interestingly this quantitative modelling revealed that the total heat losses through the walls were not reduced by the shelterbelt. The possible reason is that the reduction of the wind speed has series effects on the heat exchange on an external surface, firstly the convection, the surface temperature, then radiation heat loss. As some are contradictory result on heat dissipation from the envelope, the resultant effect of shelter trees is not significant.

A close look at the heat losses of individual rooms reveals that heat losses on the glazed areas, particularly on the North façade had various reduction rates due to sheltering effect. This suggests that the solar radiation absorption was the major reason. In reality the incidence angle of wind will surely affect convection on a wall. However in TAS this is simplified by replace the airflow velocity near the surface by wind speed measured at weather station.

# 4 Conclusions

Although this modelling study for a typical commercial building was an initial trial to estimate the effect of shelterbelts on the space heating for both commercial offices and residential buildings in Scotland, the following conclusion can be drawn.

Firstly the method of modelling wind shelter effect on thermal performance of building works reasonable well if the convection is dependent of the wind speed of a weather station. For more realistic modelling the relationship between the convection coefficient and the airflow speed needs to be locally defined.

Secondly the simulation predicted heating energy savings of 4.45% (or 2100 kWh for a floor area of ???m2 ) for a typical commercial office building in Scotland, when sheltered by a medium porosity shelterbelt located a distance of approximately 4H away from the building. For this typical two-storey cellular office space, these energy savings are equivalent to an annual $CO_2$ reduction of approximately 400 kg (assuming use of natural gas). The study also indicates the most significant energy savings were achieved as a result of reduced infiltration losses. This was found to be particularly true for the larger open spaces such as the stairwells and communal areas. Similar energy reductions may be derived in other large open spaces such as entrance lobbies which traditionally experience high levels of air infiltration.

This study so far focused at the potential benefits of shelterbelt in winter season in regard to heating saving. This is justified by the facts that the medium sized office buildings considered in this exercise in Scotland are not air-conditioned due to the mild summer. For modern offices with large glazed façade and air conditioning, the modelling has to run for a whole year to estimate the benefit. That will be next stage of this study.

This study also suggests some other further research to be done, in addition to development of a more elaborate model. First of all a more comprehensive weather statistical analysis would give more supporting for the need of reduction on space heating. It will also help understand thermal behaves of building under the weather conditions. Secondly predicted results need to be examined individually to identify the details of heat transfer and causes of physical phenomena. Thirdly the modelling method developed here should be applied to other types of buildings, such as buildings with curtain walls or large glazing facades, to evaluate the energy benefits. Similarly residential houses present a large portion of housing stock and they have a totally different occupancy, mostly they need to be heated during the night. This would potentially be benefit more from shelterbelt protection as it was suggested in the simple case test.

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