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A new methodology towards determining building performance under modified outdoor conditions

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Abstract

Great efforts have been made to establish the influence of the urban climate upon the energy consumption of buildings. While many scientific articles present measured data of increased energy consumption due to building surroundings, this paper aims to present a straightforward methodology for the assessment of building performance under modified outdoor conditions. Designers and urban planners should benefit from the results of this paper in their evaluation of proposals to decrease building energy consumption. A number of examples are discussed in order to illustrate the methodology outlined.

Keywords: Building performance; Urban environment; Climatic changes; Energy savings

1. Introduction

Urban areas have specific characteristics that contrast with those of their rural surroundings, such as urban layout, hard surfaces, traffic, absence of vegetation, etc. These differences affect the urban climate in a variety of ways due to a number of factors, as existant research demonstrates.

Landsberg [1] presents a comprehensive description of the urban climate and the principle ways in which it contrasts with the climatic conditions of the surrounding rural areas.

Oke [2] establishes a two-fold division of the urban boundary layer: the so-called urban air 'canopy', and the boundary layer over the city space known as 'the urban air dome'. Separate energy balances can then be established on the basis of this division in order to show the influence of the urban buildings in the outdoor air temperature and movement. As a result, increased air temperature is typically found in these layers, leading to the creation of urban 'heat islands'. The most important factors behind this phenomenon are summarised by Oke et al. [3].

Recent studies have attempted to identify the impact of these urban climate modifications on the energy consumption of buildings. These modifications can be classified as 'direct' or 'indirect' [4] according to their effects on buildings, which in turn permits a more straightforward and effective study of the effects themselves. Akbari et al. [5] have found that peak urban electric demand rises by 2–4% for each 1 °C rise in daily maximum temperature above a threshold of 15–20 °C. In a similar study, Santamouris et al. [6] present measured data showing that the cooling load of urban buildings may be doubled when the mean heat island intensity exceeds 10 °C.

The authors of the present article have developed a software tool designed to calculate the urban microclimate in conjunction with a building thermal

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simulation tool [7]. The overall purpose of the software is to develop an effective and straightforward methodology of analysis in order to evaluate the impact of changing conditions on the heating and cooling demands of any given building. This new methodology can be used, for example, in order to:

- Assess the 'urban heat island' effect on building energy consumption.
- Evaluate energy saving proposals regarding building surroundings.
- Expand existing software tools geared towards the development of guidelines for urban planners.

2. Heat fluxes in open spaces

The great diversity of characteristics of the open spaces surrounding buildings can modify general energy balances and consequently affect thermal performance. Furthermore, the complexity of urban configurations and annual or seasonal changes can also alter the influence of the climate over building heating and cooling demands. It has been demonstrated however, that buildings themselves are also able to modify the microclimate. A well-known consequence of this is the 'heat island effect'.

For all of these reasons, each one of the mechanisms of heat transfer through the building envelope requires specific study, taking into account both the building and its environment. The relative importance of each mechanism in comparison with others is also particular to each case and accurate results can only be obtained by using building thermal simulation programs. If we are interested in estimating the effect of a change of the building surrounding on the heating and cooling demands of a building, the thermal simulation program must be linked to an exterior conditions simulation program [8].

3. Climatic severity index (CSI)

The calculation of the heating and cooling demand of a given building requires the collection of reliable climatic data from the locality. This issue was first addressed by the 'Challenges of the Modern Society' committee in a NATO project entitled 'Climatic Conditions and Years of Reference' in 1974. The objective of this project was to recommend methods of generating climatic years of reference (TRY) for any town with sufficient climatic data. A TRY file is a group of climatic data for every hour of a whole year i.e. 8760 h [9].

A technique was later developed to characterise the severity of a certain climate for a well-known building. This technique applied the CSI particular to each building and town [10]. The advantage of this CSI in comparison to the well-known degree-days is the inclusion of external temperatures and other various climatic variables such as radiation along with the defining characteristics of the building itself in its calculations.

The CSI used in this paper is defined as the dimensionless relation between the heating or cooling demand of a given building in a specific locality, divided by a reference locality. The thermal engineering group of the University of Seville first presented this definition in a project entitled 'Dwelling Energy Labelling' [11]. Using a building thermal simulation program called Passport+, the heating and cooling demands of a large number of buildings of various types were calculated for all 50 Spanish capitals. The CSI was then calculated as the relation of those demands divided by that obtained for the same building for a specific reference locality. Madrid was found to be the best reference locality as its climate is situated in the middle of the entire range.

Two winter climatic conditions that are, in principle, *different* can be considered *identical* when the heating demand of a given building is the same in both climates. It can be said therefore, that both climatic conditions have the same *winter CSI*. The same definition can be applied to the cooling demand, in which case it can be regarded as *summer CSI*.

Furthermore, it can be said that a given climatic condition is '×' times more severe than another if the energy demand of a certain building is '×' times higher in the first case than in the second.

3.1. Validation of the climatic severity index

When the study is focussed on a certain building typology, this index is independent on the building itself with a high degree of accuracy. This can be seen in Figs. 1 and 2, where the dimensionless relations for the heating and cooling demands are shown against the corresponding CSI. This important conclusion demonstrates the usefulness of CSI.

3.2. Dependences of the CSI

This section analyses the influence of the exterior conditions over the cooling and heating demands of a given building using the concept of CSI.

Firstly, it is necessary to express the relation between the CSI and the common climatic variables. The coefficients of the four following correlations are presented in Table 1.

$$\text{winter CSI} = a\,\text{Rad} + b\,\text{DD} + c\,\text{Rad}\,\text{DD} + d\,\text{Rad}^2 + e\,\text{DD}^2 + f,$$

where DD is the mean value of the heating degree-days (December, January and February) with a base temperature of 20 °C, Rad the mean accumulated global radiation over a horizontal surface (in kWh/m^2) for the same months.

In some cases the global radiation is an unknown value, in which case another correlation must be used:

$$\text{winter CSI} = a\,\text{DD} + b\,n/N + c\,\text{DD}^2 + d\,n/N^2 + e,$$

where DD is the mean value of the heating degree-days (December, January and February) with a base temperature of 20 °C. n/N the ratio between the actual insolation hours and the maximum for each month.

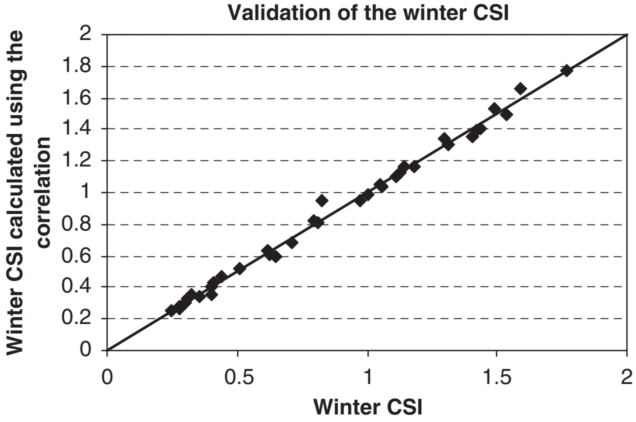

Fig. 1. Validation of the winter CSI.

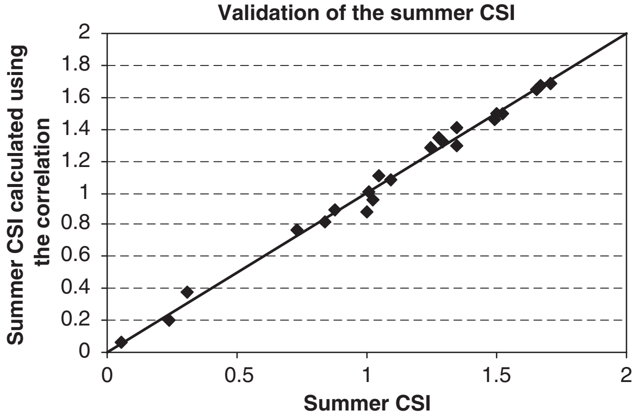

Fig. 2. Validation of the summer CSI.

For summer, the two obtained correlations are the following:

$$\text{summer CSI} = a\,\text{Rad} + b\,\text{DD} + c\,\text{Rad}\,\text{DD} + d\,\text{Rad}^2 + e\,\text{DD}^2 + f,$$

where DD is the mean value of the cooling degree-days (June, July, August and September) with a base temperature of 20 °C. Rad the mean accumulated global radiation over a horizontal surface (in kWh/m^2) for the same months.

As in the correlation of winter CSI, it is convenient to have another correlation for summer CSI:

$$\text{summer CSI} = a\,\text{DD} + b\,n/N + c\,\text{DD}^2 + d\,n/N^2 + e,$$

where DD is the mean value of the cooling degree-days (June, July, August and September) with a base temperature of 20 °C, n/N the ratio between the actual insolation hours and the maximum for each month.

4. The climate influence over the whole building

Using the CSI concept, the influence of a climatic variable change over the cooling and heating demands of a certain building can be estimated, assuming that this change affects the whole building in the same way. A typical modification like this is the variation of the external air temperature since it modifies the degree-days. The effect of this variation on the building is called ‘indirect effect’ (see [4]) since it is not due to the building itself but rather to the urban climate variation.

An increase of the heating or cooling degree-days (ΔDD), can be expressed as an increase of the CSI, (ΔCSI) [12]:

$$\begin{aligned}\text{CSI} + \Delta\text{CSI} &= a(\text{DD} + \Delta\text{DD}) + b\,n/N \\ &\quad + c(\text{DD} + \Delta\text{DD})^2 + d\,n/N^2 + e \\ &= a\,\text{DD} + b\,n/N + c\,\text{DD}^2 \\ &\quad + d\,n/N^2 + e + a\,\Delta\text{DD} \\ &\quad + c\,\Delta\text{DD}^2 + 2c\,\text{DD}\,\Delta\text{DD}\end{aligned}$$

and then

$$\Delta\text{CSI} = \Delta\text{DD}(a + c(\Delta\text{DD} + 2\text{DD})).$$

Table 1
Coefficients of winter CSI and summer CSI correlations

		a	*b*	*c*	*d*	*e*	*f*
Winter CSI	DD and Rad	−8.352E-03	3.721E-03	−8.624E-06	4.8833E-05	7.148E-07	−6.814E-02
	DD and *n*/*N*	2.395E-03	−1.111	1.885E-06	7.026E-01	5.709E-02	
Summer CSI	DD and Rad	3.724E-03	1.409E-02	−1.869E-05	−2.053E-06	−1.389E-05	−5.434E-01
	DD and *n*/*N*	1.090E-02	1.023	−1.638E-05	−5.977E-01	−3.370E-01	

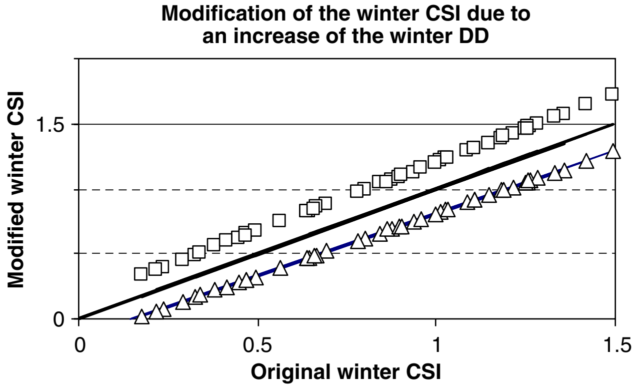

Fig. 3. Modification of the winter CSI.

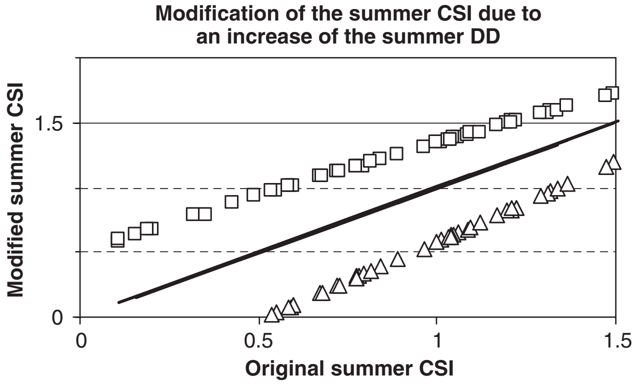

Fig. 4. Modification of the summer CSI.

For example, in Figs. 3 and 4 the modifications of the CSI provided by two different variations of the heating and cooling degree-days are shown. In these figures, three lines of modified CSI are contrasted with the original CSI: without any modification (gross line), with an increase of 50 DD (squares) and with a decrease of 50 DD (triangles).

5. The climate influence over each building envelope component

When the climate modification does not affect the whole building in the same way, it is necessary to study the influence over each building envelope component separately. An example of the latter is a modification of the external air temperature, the effects of which have been explored in the previous section. However, a variation of the incident solar radiation or the surface temperature, affects each building envelope component in different ways, depending on the orientation of component, etc.

For the purposes of this study, the contributions of each element to the total heating and cooling demands must be known. These contributions depend on the building type, the climate, the orientation of the element and its thermal properties. In terms of a certain building type, it is therefore possible to obtain correlations in order to estimate the average contribution to the demands as a function of the rest of the variables. The coefficients of the following two correlations appear in Table 2:

$$\text{Wall or window contribution } (\mathrm{W/m^2}) = (a\,\mathrm{DD} + b\,\mathrm{TR}(L-d) + c)U,$$

where U is the global thermal transmittance of the exterior wall or window in $\mathrm{W/m^2\,^\circ C}$, DD the heating or cooling degree days for the considered month, with a base temperature of 20 °C, TR the total incident radiation over the exterior wall or the window, for the considered month, in W, $L-d$ the difference between the latitude and the monthly solar declination.

Similarly, the solar heat gains through a window can be estimated using the following correlation:

$$\text{Solar gains } (\mathrm{W/m^2}) = (a\,\mathrm{TR} + b\,\mathrm{TR}\,(L-d))\mathrm{SC},$$

where SC is the window shading coefficient.

Using the previous correlations, it is possible to estimate the influence of a climatic variable change over the contribution of the components to the cooling and heating demands of a certain building. Typical modifications would be, for example, a variation of incident solar radiation or of surface temperature due to factors such as a colour change of the exterior surface or the installation of new shading devices. The effect of this kind of variation on the building is called 'direct effect' (see [4]) , since it is due to the building itself as opposed to a variation in the urban climate.

An increase of the incident solar radiation (ΔTR), can be expressed as an increase of the *Wall or window contribution* (see [4]):

$$\begin{aligned}&\{\text{Wall or window contribution}\}\\&+\Delta\{\text{Wall or window contribution}\}\\&\quad=(a\,\mathrm{DD}+b(\mathrm{TR}+\Delta\mathrm{TR})(L-d)+c)U\\&\quad=(a\,\mathrm{DD}+b\,\mathrm{TR}(L-d)+c)U\\&\qquad+b\,\Delta\mathrm{TR}(L-d)U\end{aligned}$$

Table 2
Coefficients of element contribution correlations

		a	*b*	*c*
Wall contribution	Winter	−7.492E-01	1.142E-04	−7.860E+00
	Summer	1.042E+00	3.912E-04	−1.412E+02
Window contribution	Winter	−6.646E-01	−1.508E-04	−5.575E+01
	Summer	9.867E-01	3.401E-05	−1.755E+02
Solar gains	Winter	5.857E-01	1.681E-03	
	Summer	6.021E-01	1.157E-03	

and then

$$\Delta\{\text{Wall or window contribution}\} = b\,\Delta\text{TR}(L-d)U.$$

However, solar gains are also modified by an increase in incident solar radiation:

$$\begin{aligned}\{\text{Solar gains}\} + \Delta\{\text{Solar gains}\} &= (a(\text{TR}+\Delta\text{TR}) \\ &\quad + b(\text{TR}+\Delta\text{TR})(L-d))\text{SC} \\ &= (a\,\text{TR} + b\,\text{TR}(L-d))\text{SC} \\ &\quad + (a\,\Delta\text{TR} + b\,\Delta\text{TR}(L-d))\text{SC}\end{aligned}$$

and then

$$\Delta\{\text{Solar gains}\} = (a\,\Delta\text{TR} + b\,\Delta\text{TR}(L-d))\text{SC}.$$

For example, in Figs. 5 and 6, the wall and window contributions to the heating demand are contrasted with the CSI. Figs. 7 and 8 correspond to the cooling demand. In this example the heating demand has been calculated for the months of December, January and February, and the cooling demand for June, July, August and September. The thermal properties of the wall and the window are: $U_{\text{wall}} = 1\,\text{W/m}^2\,{}^\circ\text{C}$, $U_{\text{window}} = 5.7\,\text{W/m}^2\,{}^\circ\text{C}$ and $\text{SC}_{\text{window}} = 1$. The values corresponding to northern elements are represented by triangles; those corresponding to southern elements by squares and finally, values corresponding to negligible incident solar radiation are represented by circles.

6. Analysis of building performance under modified outdoor air temperature

This section examines how the methodology can be implemented to determine the influence of modified outdoor air temperature.

The CSI index can be used to relate the heating and cooling energy demand of a building to ambient air

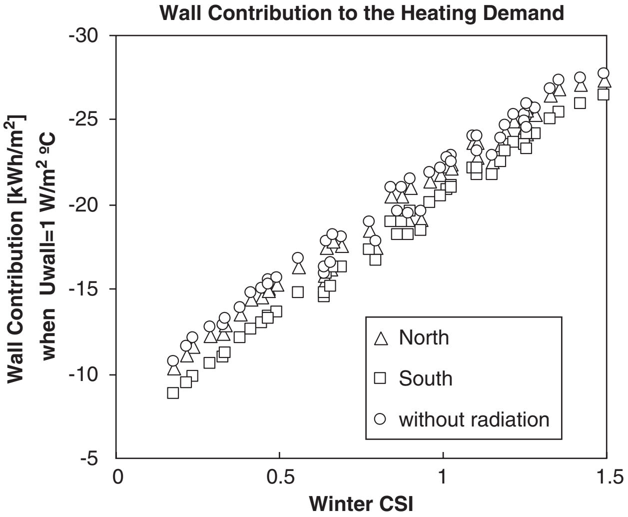

Fig. 5. Wall contribution to heating.

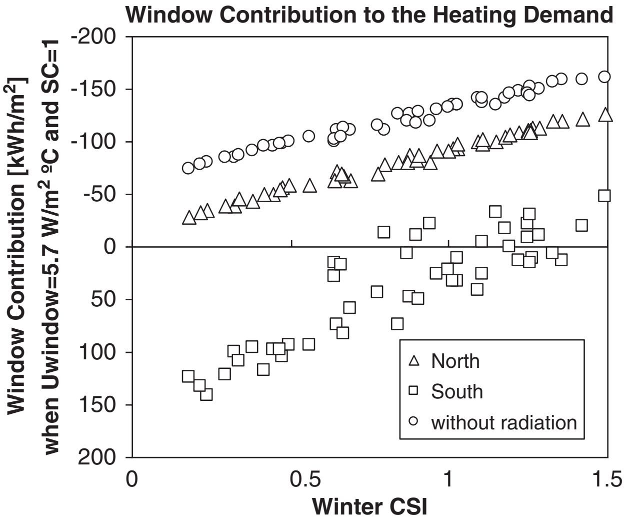

Fig. 6. Window contribution to heating.

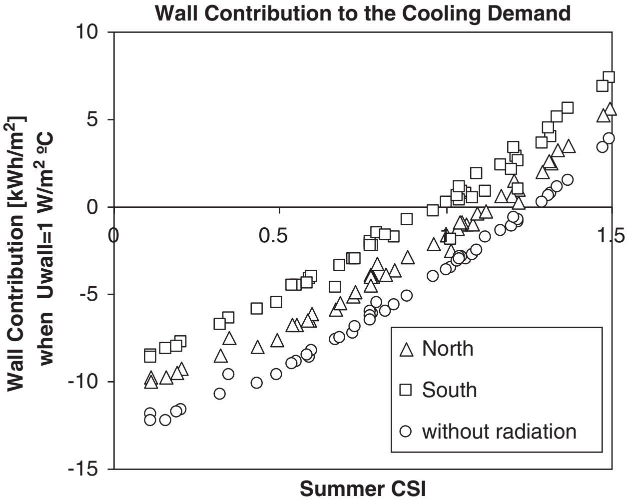

Fig. 7. Wall contribution to cooling.

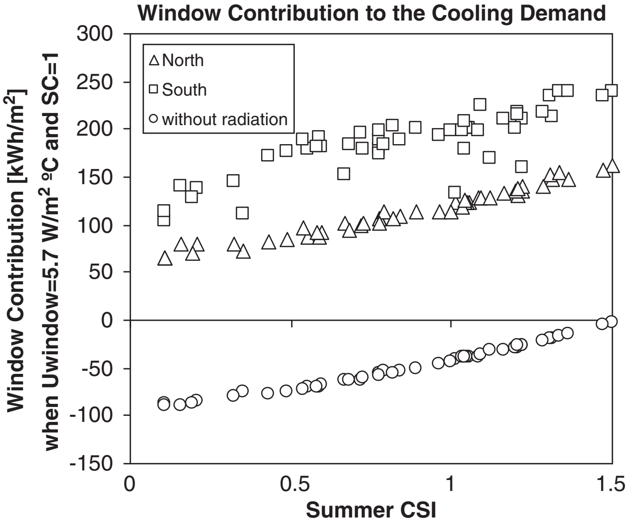

Fig. 8. Window contribution to cooling.

temperature; assuming that ambient air temperature has the same value around the building (irrespective of orientation), any change must affect the energy demand of the building in the same way.

When the climatic change affects particular parts of a building as a result of a function of the orientation for example, the previous methodology cannot be applied; this methodology requires that the whole building be considered. In order to examine the climatic effects on particular parts of the building such as exterior walls and windows, the energy demand of these individual components must be calculated. A typical climatic variable that affects the individual components of a building in a different way is solar radiation. As was the case in our previous examination of climate influence over the total building energy demand (see [4, p. 7]), it is possible to obtain the increase of each contribution as functions of the climatic variables and their increments.

The effect of a modification in urban air temperature over the heating and cooling energy demands of a given building depends on the climatic conditions, and on the very characteristics of the building itself.

Using the methodology introduced for the evaluation of the climate influence on the total building demand, it is possible to obtain the variation of the CSI as a function of the air temperature increment.

For example, assuming that a certain urban context is responsible for an average air temperature decrease of 10°/h by day during the cooling period (base temperature for the DD calculation is 20 °C), as a direct consequence it can be calculated that $\Delta DD = -12.7$. Assuming also that the building is located in Seville (Spain) where $DD = 175.61$, and $CSI = 1.51$, then the CSI modification is $\Delta CSI = -0.07$, and consequently $CSI_{modified} = 1.44$.

This result can be interpreted in two ways. Firstly, following the CSI definition, it can be said that the building performance in this modified urban context will be the same as that of the corresponding building performance in a non-modified urban context in another location, where $CSI = 1.44$. This could be approximately the value of Jaén (Spain). Secondly, taking into account the fact that the CSI is a dimensionless energy demand, these values can be used to obtain the real values and, in turn, the energy saving as a result of the climatic modification, in this case 6%.

A sensitivity analysis of the savings in cooling demands that can be achieved as a result of the decrease in mean air temperature (using the previous location and value) is shown in Figs. 9 and 10. It is clear from these examples that the savings are proportional to the mean decrease in outdoor air temperature. Notably, the colder the city, the higher the saving i.e. it is inversely proportional to the CSI (Seville: 1.51, Madrid: 1, Burgos: 0.43).

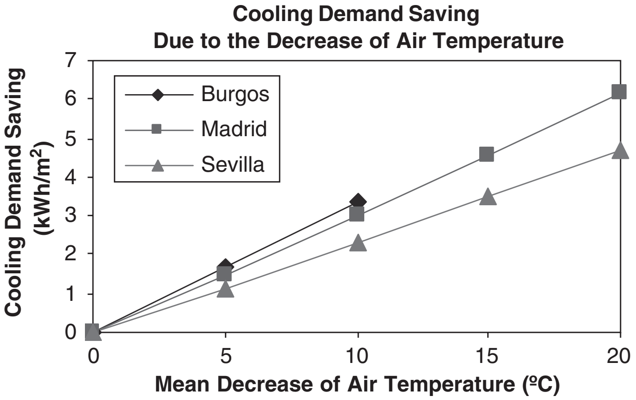

Fig. 9. Absolute saving of cooling demand.

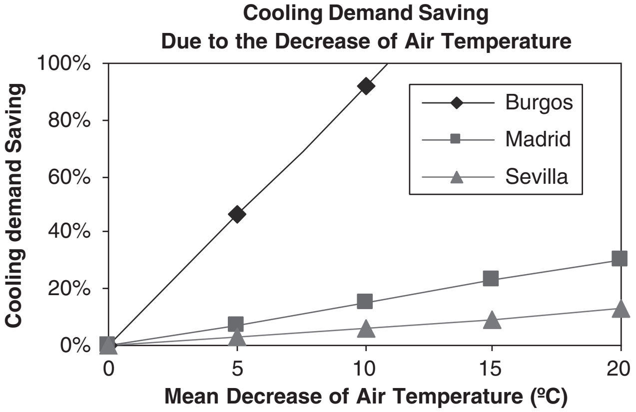

Fig. 10. Relative saving of cooling demand.

7. Analysis of building performance under modified incident solar radiation

This section describes how this technique can be implemented in relation to a change in incident solar radiation.

The effect of a modification of solar radiation on the building energy demand due to urban context must be calculated for each external component (walls and windows), since this modification affects each component in a different way. It is necessary therefore, to use the methodology introduced above, while at the same time considering the climate influence on the contribution to the building energy demand by components.

For example, let us assume that the impinging solar radiation over the south façade of a certain building is decreased by 10% of the original value as a result of urban context modifications such as new surfaces providing shade, low albedo materials, etc. If for instance, the façade is composed of a wall of thermal global transmission coefficient $U = 1\,W/m^2\,°C$, and of a window with $U = 5.7\,\mathrm{W/m^2\,^\circ C}$ and shading coefficient $SC = 1$; then the energy saving in terms of the contribution of this façade to the demand for the building can be estimated.

Figs. 11 and 12 show the decrease of this contribution assuming the building is located in Seville and taking into account three different percentages of glazing in the façade (10%, 50% and 90%). The first figure represents the absolute values and the second the relative values. In both figures, the *x*-axis refers to the percentage of the original incident solar radiation i.e. a value of 100% means that there is no reduction.

As can be observed, the decrease variation is proportional to the original impinging solar radiation; if it were to be compared to other locations, almost the same absolute values would be obtained, as the variation of the total solar radiation is very small given the latitude range considered (Seville: 37.4, Madrid: 40.41, Burgos: 42.3). Another important conclusion is that this saving is greater when percentage of glazing in the façade is higher.

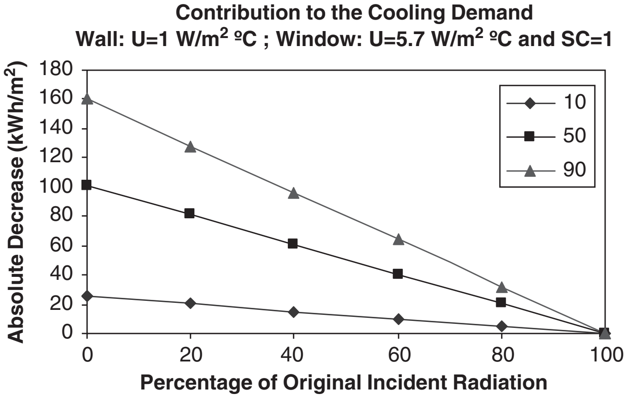

Fig. 11. Absolute decrease of contribution to the cooling demand.

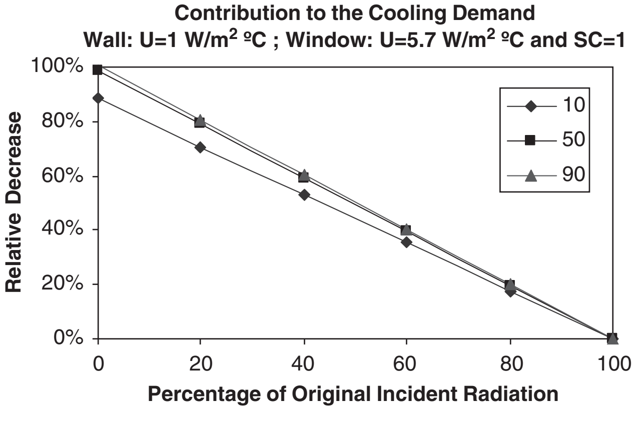

Fig. 12. Relative decrease of contribution to the cooling demand.

8. Analysis of building performance under modified surface temperature

This section examines how the methodology can be implemented to determine the influence of modified surface temperature.

The effects of a modified surface temperature are more complex than in the previous cases considered. On the one hand, if the surface belongs to the building under consideration, then its temperature will modify the heat flux only by conduction. On the other hand, if this surface belongs to other side buildings or nearby roads for example, then it can modify both: the heat flux by long-wave radiation and the outdoor air temperature.

The first effect is due to the modification of the surface albedo, which has been addressed in the solar radiation section above. The modification of the outdoor air temperature has also been studied therefore, the only remaining effect is that of long-wave radiation modification.

In this case, it is possible to use the analogy between the surface temperature and the air temperature in terms of the concept of equivalent temperature defined as follows:

$$t_{\mathrm{eq}} = \frac{h_{\mathrm{c}} t_{\mathrm{a}} + h_{\mathrm{r}} t_{\mathrm{r}}}{h_{\mathrm{cr}}},$$

where h_{c} is the outdoor convective transfer coefficient, h_{r} the outdoor radiant transfer coefficient, h_{cr} the outdoor convective-radiant transfer coefficient $h_{\mathrm{cr}} = h_{\mathrm{c}} + h_{\mathrm{r}}$, t_{a} the outdoor air temperature, t_{r} the outdoor radiant temperature.

It is possible to express the relation between the concepts of radiant temperature and radiant heat transfer coefficient using these factors, the surface temperature and air temperature.

$$t_{\mathrm{r}} = \mathrm{FF}_{\mathrm{sky}} t_{\mathrm{sky}} + (1 - \mathrm{FF}_{\mathrm{sky}}) t_{\mathrm{suf}},$$
$$h_{\mathrm{r}} = 4\sigma[t_{\mathrm{r}} + 273.15]^3,$$

where σ is the Stefan–Boltzmann constant $\sigma = 5.67\,e{-}8\,\mathrm{W/m^2\,K^4}$, t_{suf} the mean surface temperature, t_{sky} the sky temperature, $\mathrm{FF}_{\mathrm{sky}}$ the form factor with the sky.

Therefore, an increment in surface temperature, Δt_{suf}, shows an increment in radiant temperature, $\Delta t_{\mathrm{r}} = (1 - \mathrm{FF}_{\mathrm{sky}})\Delta t_{\mathrm{suf}}$, that can be expressed in terms of an increment in equivalent temperature, $\Delta t_{\mathrm{eq}} = h_{\mathrm{r}}/h_{\mathrm{cr}}\,\Delta t_{\mathrm{r}}$. The same increment can be obtained by modifying the air temperature instead of the surface temperature. We can then conclude that $\Delta t_a \equiv (h_{\mathrm{r}}/h_{\mathrm{c}})\Delta t_{\mathrm{r}}$.

Assuming $h_{\mathrm{c}} \cong 20\,\mathrm{W/m^2\,^\circ C}$, and $h_{\mathrm{r}} \cong 5\,\mathrm{W/m^2\,^\circ C}$, then $\Delta t_{\mathrm{a}} \cong (1/4)\Delta t_{\mathrm{r}}$ and finally if the sky form factor equals 0.5

$$\begin{aligned}\Delta t_{\mathrm{a}} &= (h_{\mathrm{r}}/h_{\mathrm{c}})(1 - \mathrm{FF}_{\mathrm{sky}})\Delta t_{\mathrm{sup}} \\ &\cong (1/4)0.5\,\Delta t_{\mathrm{sup}} = (1/8)\Delta t_{\mathrm{sup}}.\end{aligned}$$

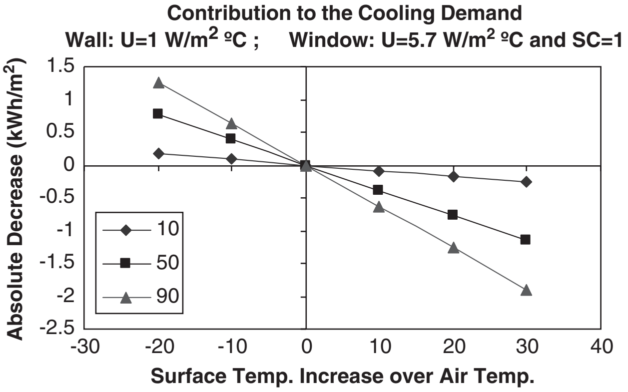

Fig. 13. Absolute decrease of the cooling demand.

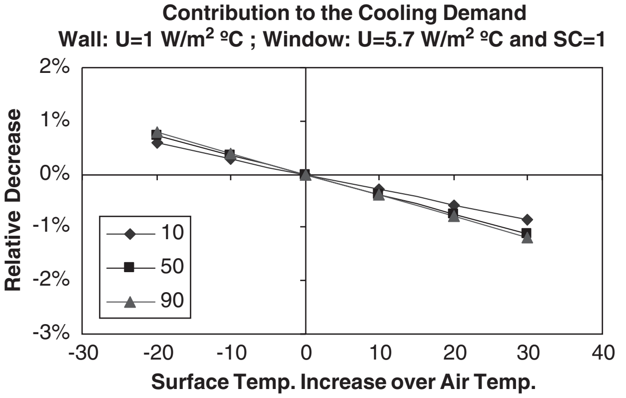

Fig. 14. Relative decrease of the cooling demand.

Therefore, the methodology used to determine the influence of a modification in air temperature can also be applied in this case.

The absolute and relative decrease of the total cooling demand can be represented for the previous example as a function of the increment in surface temperature. As can be seen in Figs. 13 and 14, the savings are higher for higher window to wall ratio. The savings are nonetheless, very low in all cases.

9. Conclusions

Energy consumption of buildings is related to factors of urban climate such as solar loads, wind flow patterns and external air temperature. Improvements in urban microclimate should therefore, have direct and indirect consequences on energy savings.

The methodology outlined in this paper facilitates a fast and straightforward analysis of building performance as a function of outdoor conditions and should prove invaluable for designers, urban planners and other professionals in related fields.

Furthermore, this methodology has as its major advantage a quick and easy to use assessment tool of the effect influence of the 'urban heat island' effect on the building energy consumption. Additionally, designers or urban planners, have the possibility of evaluated their proposals of changing the building surrounding in order to decrease the building energy consumption.

Different examples have been shown in the present paper. Thus, the presented methodology has been useful to obtain quantitative results for the influence of the outdoor air temperature decrements, the reduction of solar radiation, and the variation of surface temperatures.

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