CONDENSATION TARGETER: THE INTEGRATION OF A THERMAL AND MOISTURE MODEL

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Abstract

This paper describes a design tool, 'Condensation Targeter, for assessing condensation risk in dwellings and the effect of remedial measures thereon. The BREDEM energy model is augmented by a moisture model to determine mean internal relative humidity (MIRH). This measure of condensation risk is calculated for two zones in a dwelling from mean internal temperatures, moisture generation and ventilation rates. Primary input data relate to occupancy (fuel expenditure and moisture production) and dwelling characteristics (thermal and ventilation). MIRH results are presented as a function of space heating input for an example dwelling with remedial measures applied (insulation and extract fans). The constraints imposed by household income and the implications for condensation risk are discussed. Comparisons between model predictions and monitored results are discussed as is the sensitivity of predictions to the accuracy of input data.

1 Introduction

Mould growth occurs in 10 to 20% of housing in the UK and several other European countries. Considerable funds are now being allocated to the refurbishment of these buildings. At present some of this money is misdirected, as mistakes are made in the design and installation of anti-condensation measures. One reason for error is the lack of adequate design tools for making decisions on the best means of remedying condensation and mould growth in particular dwellings.

Research at many institutions around the world is now leading to a better understanding of the mechanisms causing condensation and mould growth. However, few comprehensive design tools are available which contain the most up-to-date thinking on remedial measure design.

This paper outlines one way of addressing these problems through a combined energy and condensation model. The BREDEM energy model(1) has been enhanced by incorporating Loudon's condensation model(2). The final objective of this work has been to produce a computer package for use by building designers when refurbishing housing. This calculates the risk of condensation within dwellings using two main parameter inputs; dwelling characteristics and type of occupant (e.g. pensioners, unemployed families, single persons etc.) as illustrated in Figure 1. Remedial measures (e.g. draught stripping, central heating, etc.) can then be compared for their effect on condensation risk.

Condensation risk is here taken to mean both the risk of surface condensation and the risk of mould growth due to high humidity conditions on a surface without liquid water present.

2 Model Selection

A condensation risk prediction model which can analyse the effects of changes to building design, moisture control and fuel expenditure requires components which determine the temperature and moisture content of the air inside the dwelling. In practice two integrated models are required; a thermal model and a moisture model.

Current thermal models which deal with energy consumption and internal temperatures in buildings range in complexity from those based on steady-state heat loss for hand calculation to large dynamic simulation models requiring mainframe computers. The latter are all complex and are unsuitable for use as design tools. However, several simple but sophisticated models have been developed to predict annual energy consumption. The Building Research Establishment (BRE) have designed the core of such a model, called BREDEM(1), which the present authors considered to be the best vehicle for a condensation risk model. A major advantage is the availability of a very 'user friendly' implementation of version BREDEM-5, which is commercially available as the 'Energy Auditor' computer package(3). The latter is already widely used as a design tool on refurbishment projects.

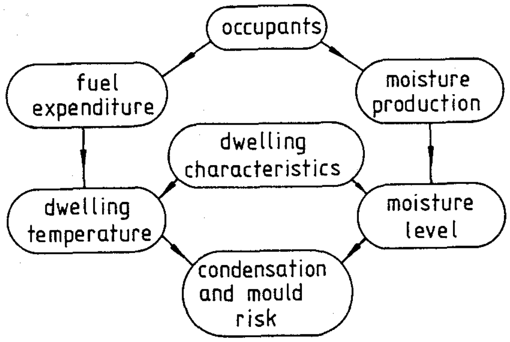

Figure 1 Model for condensation risk prediction

BREDEM is a two-zone modified degree-day model which accounts for casual and solar gains, and the efficiency and responsiveness of a variety of heating systems. 'Energy Auditor' was specifically designed for examining the energy savings associated with improvements to the building fabric and heating system of existing buildings. The accuracy of 'Energy Auditor' has been tested and reported by Henderson and Shorrock(4).

Much less work has been done on moisture and condensation models than on thermal models, since energy has been far more of a national issue than condensation during the past two decades. The most generally accepted model for prediction of surface condensation and mould risk is that due to Loudon(2). This model uses just two steady-state equations to determine mean internal relative humidity (MIRH); one for energy balance and one for moisture balance in a dwelling or zone. Condensation risk is considered to be unacceptably high if the MIRH in the space exceeds 70%. This work has helped to improve understanding of the interactions between the many factors involved in condensation; it has recently been introduced into a draft revision of BS 5250(5) as a simple design tool. The present authors have therefore chosen to incorporate a moisture balance equation into BREDEM.

3 Interaction of thermal and moisture models

The dwelling is treated as two separate zones as set out in BREDEM: the 'living area' taken as Zone 1 and the 'rest of the house' as Zone 2. The kitchen may be allocated to Zone 1 or Zone 2 depending on the layout of the particular dwelling. The thermal model calculates the mean internal temperature (MIT) of each zone, whole house ventilation rate and energy consumption over the heating season. The moisture model calculates mean internal vapour pressure for given moisture generation and ventilation rates in each zone. The division of the dwelling into two zones is an improvement on whole-house assessment since it allows modelling of different modes of heating and moisture production in different parts of the home. The structure of the model is shown schematically in Figure 2.

3.1 Vapour pressure

The steady-state approach assumes that within a given space the moisture generation rate is equal to the rate of moisture removal by air vented to outside less that returned by the make-up air. Internal vapour pressure, as given in the draft BS 5250(5), is then:

$$P_i = P_e + \frac{W}{0.191\,N\,V} \qquad (1)$$

where P_i and P_e are the mean internal and external vapour pressure (kPa), W is the rate of moisture emission (kg day^{-1}), V is the space volume (m^3) and N is the ventilation rate (h^{-1}). This equation is an approximation since prediction of internal vapour pressure is strictly dependent on the density of internal and external air. However, for the present purposes the errors involved are less than 3% in the MIRH which is not significant compared with the uncertainties in other input parameters, e.g. moisture production, ventilation rate, etc.

The moisture generated each day in the dwelling is dependent on occupancy and the appliances used (e.g. gas cooker, tumble drier). BS 5250(6) lists typical moisture generation rates for householder activities and for heating appliances. These have been combined with occupancy periods to define the daily moisture generation rates shown in Table 1. The way in which this total moisture generation is distributed between two zones of the dwelling is critical for condensation risk assessment. Rooms in

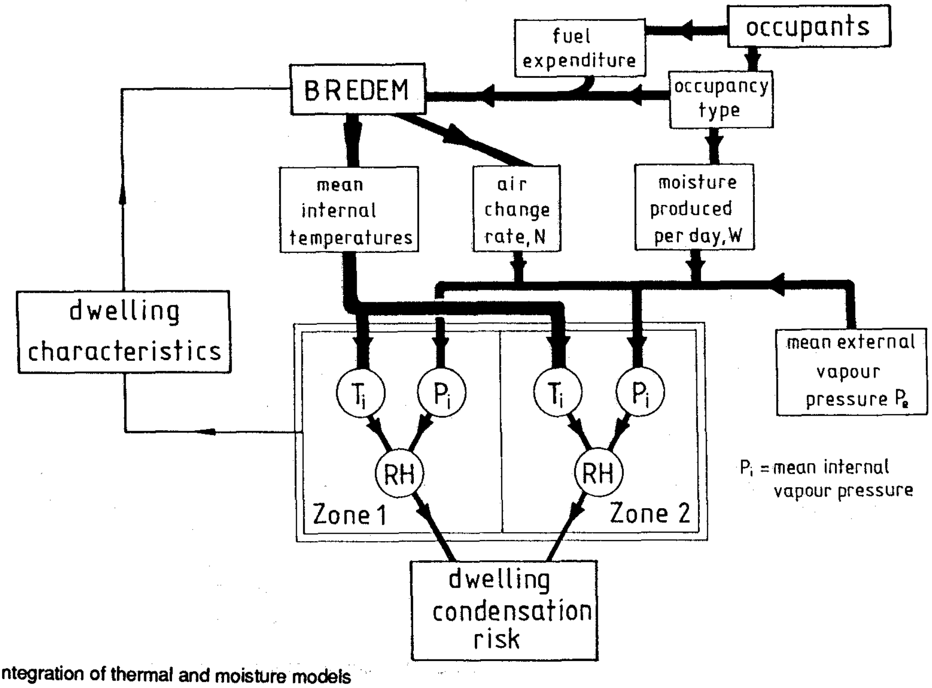

Figure 2 Integration of thermal and moisture models

Table 1. Daily moisture generation for various activities

Origin	Regime	Contribution
Metabolic	Day	1/2 No. of occupants x Occupancy period x 0.055 kg h^{-1} $person^{-1}$
	Night	No. of occupants x 7 h x 0.04 kg h^{-1} $person^{-1}$
Kitchen	Electric cooking	2 kg day^{-1}
	Gas cooking	3 kg day^{-1}
	Dishwashing	0.4 kg day^{-1}
Bathroom	Bathing/washing	No. of occupants x 0.2 kg $person^{-1}$ day^{-1}
	Clothes washing	0.5 kg day^{-1}
Heating	Bottled gas or paraffin only	Total rating x Occupancy period x 0.1 kg kWh^{-1}

Zone 2 will generally be at most risk since they are usually less well heated than the living room (e.g. bedrooms) and/or contain the areas of greatest moisture generation (e.g. kitchens and bathrooms). Total daytime metabolic moisture generation is calculated assuming that half of the occupants are present in the dwelling for the whole of the heating period. The metabolic moisture is apportioned equally between the two zones, the other moisture sources are allocated to a particular zone.

Determination of mean internal vapour pressure is very sensitive to the chosen value of P_e. The second term on the right-hand side of equation 1 is small compared with P_e. From modelling and monitoring data it is of the order of 0.3 kPa in occupied dwellings. Thus relatively small changes in the values of P_e may have large effects on absolute condensation risk. Mean external vapour pressure varies according to the geographical location of the dwelling. For the UK, average heating season values vary from 0.72 kPa (N.E. Scotland) to 0.94 kPa (S.W. England).

3.2 Mean internal temperature

BREDEM determines space heating fuel consumption and cost by utilising the mean internal temperatures (MITs) calculated for Zones 1 and 2. These MITs are then used with vapour pressure to determine mean internal relative humidity (MIRH) for condensation risk assessment. MIT is defined as the 24 h mean temperature averaged over all days in the heating season on which space heating is required. BREDEM accounts for different heating patterns in Zones 1 and 2 resulting from different lengths of occupancy and different levels of heating that occupants live under because of their status (employed/unemployed, retired etc.). Recent field studies(7) have provided substantive data on periods of dwelling occupation by various groups and the metabolic activity rates during these periods. The MIT in each zone is also determined by casual heat gains and the responsiveness of the heating system.

Several reservations must be attached to the use of the mean internal temperature as derived by BREDEM. For example, it is possible that MITs calculated by BREDEM have a more critical influence on condensation risk than on the calculation of annual space heating load. Of particular note are the assumptions regarding fixed casual gains, inter-zone heat transfer, and outside temperature. These limitations are currently being investigated.

3.3 Ventilation rate

The calculation of the long-term ventilation rate of any building is complicated, and seldom accurate even using the most sophisticated and detailed models. 'Energy Auditor' calculates air change rates by using four components of ventilation: (a) opening infiltration; (b) flues and chimneys; (c) suspended timber floors, and (d) background due to fabric leaks and deliberate ventilation. Each of these has a set value or requires the use of an algorithm based on the dwelling characteristics. This method is heuristic and cannot be improved without compiling much more detailed information on a dwelling and its occupants. It allows the separation of effects of various components which might occur in a refurbishment and which could significantly affect condensation risk.

3.4 Extract fans

Of all the active measures available to reduce condensation risk in a dwelling, extract fans are widely considered the most successful and least expensive, although maintenance is often seen as a problem. It is thus important to assess the effect of extract fans in kitchens and bathrooms. When natural ventilation is being considered then it is assumed that all moisture generated in the kitchen and bathroom is distributed throughout the zone to which they are allocated. Extract fans are normally attributed with two effects which changes this situation: moisture laden air is removed to the outside immediately it is produced during activities such as cooking and washing, thereby reducing the room vapour pressure; The amount of moist air which migrates from the room to the rest of the dwelling is reduced (since the room is depressurised). However, most domestic fans cannot prevent moisture migration through open doors because of thermally induced air movement(8).

For present purposes it has been assumed that fan operation can be modelled by using the effective reduction in actual daily moisture input for a given activity to calculate a reduced moisture generation rate. The latter is determined by considering the mean room vapour pressure under natural and mechanically assisted ventilation regimes(9). Typically, for a dwelling with extract fans in the kitchen and bathroom it is assumed that the extract fan will remove 80% of moisture produced by cooking and bathing.

4 Assessment of condensation risk

4.1 Influence of dwelling characteristics

An assessment of condensation risk must be made from the mean internal relative humidity (MIRH) of the two zones in the dwelling. Within a real occupied dwelling the risk of condensation or mould growth will vary widely due to spatial and temporal effects. BS 5250 asserts that the condensation risk will be unacceptably high when MIRH exceeds 70%. The validity of this limit is open to question, however, it does seek to account for differences between conditions in the bulk air of a room and those on the inside of external surfaces and for the fact that mould may grow where surface RH is less than 100%. Measurements in environmental chambers have shown that mould grows on wall covering materials if the relative humidity is greater than 80% for a period of several days(10).

In this paper a value of MIRH=70% has been taken as critical with regard to condensation risk. However, this will underestimate the condensation risk in certain dwellings where the surface temperatures are low so that the surface RHs are greater than 80% with a MIRH lower than 70%. For example, external walls with U-values greater than 1.2 $Wm^{-2}K^{-1}$ or thermal bridges in well insulated walls may a have low surface temperatures which will result in mould growth at a MIRH of less than 70%(11).

4.2 Influence of occupant income

Condensation is critically dependent on dwelling MIT which relates to occupant income through space heating input. For low income groups the amount of money and thus fuel available for space heating is limited. Hence, dwelling MITs decrease with decreasing income as confirmed by a number of studies(12)(13). Field study(13) data has shown that decreasing income leads to a progressive fall in the temperature of Zone 2, while that in Zone 1 remains relatively constant. This implies that people with limited resources maintain a comfortable temperature in their living room while either reducing the heated area in the rest of the dwelling or reducing the temperature at which the latter is maintained.

BREDEM is uniquely structured to model this practice. A number of BREDEM calculations can be performed for different areas of heating in Zone 2 and decreasing demand temperature in Zone 1. The way in which the BREDEM model simulates the field study data is seen by comparison of Figures 3 and 4.

5 Use of model

The integrated thermal and moisture models have been applied to a specific building to illustrate the operation of the condensation prediction method. To facilitate comparison of results with those of earlier studies, a mid-terrace two-storey house with the same construction as the example house used by Loudon(2) was analysed. Constructional and thermal details are given in Table 2.

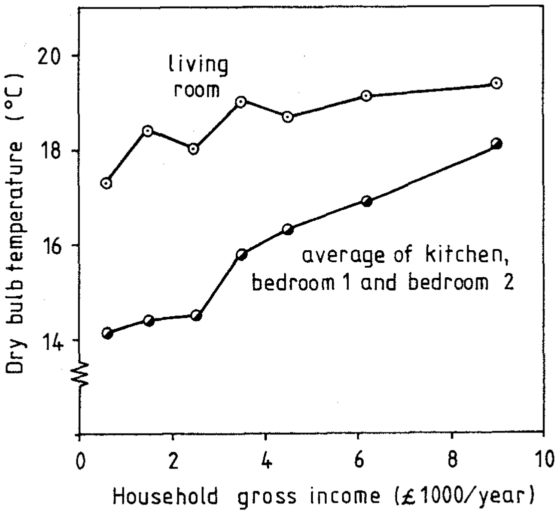

Figure 3 Measured dwelling zone temperatures as functions of household income(13)

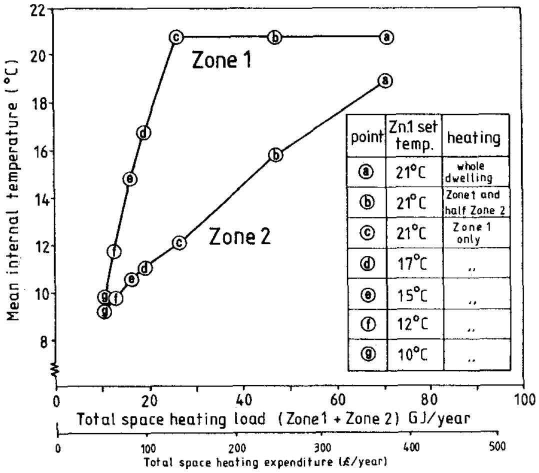

Figure 4 Zone MITs as functions of total dwelling annual space heating load calculated by 'Energy Auditor' for a four-bedroom electrically heated flat

Table 2. Details of house modelled (3-bed 2-storey terrace house, 2 adults + 3 children, gas CH, total volume=206 m^3, Zone 1 volume=45.6 m^3, degree days=2500, P_s=0.83 kPa)

Building element	U-value ($Wm^{-2}K^{-1}$)	Gross area(m^2)	Zone 1 area(m^2)
External Wall	1.7	41.0	15.0
Roof	1.4	43.0	0.0
Floor	0.8	43.0	19.0
Glazing	5.0	16.0	5.0
Doors	2.4	3.0	

Two generic types of remedial measure are available for combating condensation in dwelling: those which increase mean internal temperature and those designed to reduce internal vapour pressure. An example of insulation (i.e. a measure which increases the MIT) is shown in Figure 5, a comparison between the house detailed in Table 2 and an insulated version with external walls insulated (U-value 0.6 $Wm^{-2}K^{-1}$) and insulation added to the roof (U-value 0.35 $Wm^{-2}K^{-1}$). Moisture production is unaffected by the addition of insulation and condensation risk is therefore reduced for a given annual heat input. Taking the original mid-terrace house to be occupied by two adults and three children producing 8.5 kg day^{-1} of moisture, MIRH of 70% in Zone 2 is maintained for a total space heating load of approximately 52 GJ y^{-1}. The space heating required to maintain the same conditions in the insulated house is reduced by more than half to 25 GJ y^{-1}.

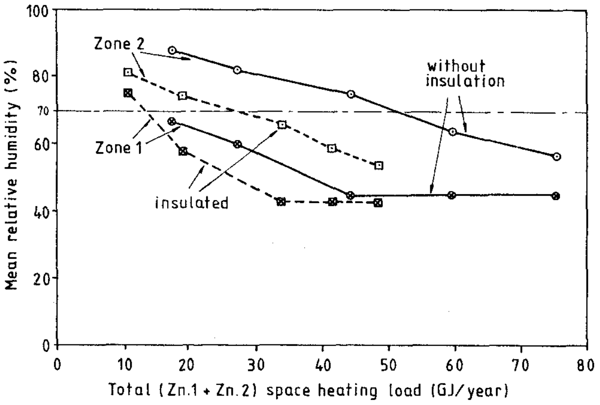

Figure 5 Zone MIRH for standard and insulated versions of two-storey mid-terrace house (occupied by a five-person family)

Remedial measures which effectively reduce the input of moisture to the dwelling include the installation of kitchen and bathroom extract fans. Figure 6 illustrates the effect of this in the case of the unmodified house occupied by a five-person family. It is assumed that extract fans are fitted in the bathroom and kitchen which remove 80% of the moisture produced by cooking and bathing. The effect of the fan is to reduce the MIRH in Zone 2 by approximately 10% for a given space heating load. The corresponding decrease in the space heating fuel requirement to avoid condensation is 40%.

A more complex measure like draught stripping affects both MIT and vapour pressure. For a relatively leaky house with a mean ACR of 2.0 h^{-1} occupants must supply 52 GJ y^{-1} total space heating to avoid condensation in Zone 2. If draught stripping were applied and the ACR reduced to 0.5 h^{-1}, MITs are significantly increased by about 4°C for the same energy input. However, condensation risk is increased, not reduced, because of the accompanying rise in internal vapour pressure. In fact to avoid the condensation risk in Zone 2 heat input must be increased by about 27%.

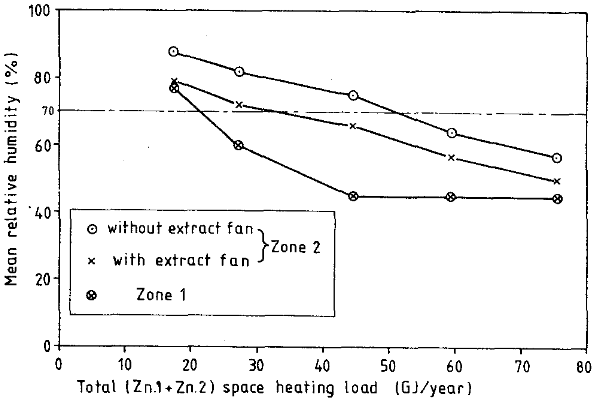

Figure 6 Zone MIRH for a typical two-storey mid-terraced house with and without extract fans in kitchen and bathroom (five-person family)

Designers require data on income available for space heating for different types of household. In general terms, low-income households spend proportionately more on fuel than those of higher incomes(9). To estimate income available for space heating, one must make some judgment as to how a household apportions its fuel expenditure. As a first step it could be assumed that fuel expenditure for functions other than space heating (i.e. lighting, water heating, appliances, cooking, etc.) is independent of gross income.

It is important that designers are aware of how little households have to spend on fuel and how this relates to condensation risk. Consider a five-person family living in the house described above. If the two adults were unemployed the household income from supplementary benefit payments would only be £113 per week. On average they would only spend £9.29 per week or £483 per year of this on fuel(9). The total cost of hot water heating, cooking, standing charges, lights and appliances as calculated by 'Energy Auditor' is £380 per year, leaving the hypothetical family with £103 per year to spend on space heating. This is equivalent to a heating load of 28.6 GJ y^{-1} (with gas central heating). Reference to Figure 5 shows that this family could not afford to heat their home sufficiently to avoid condensation without the installation of remedial measures such as wall insulation.

6 Discussion

The tool outlined in this paper enables designers to assess the condensation risk which might result from dwelling refurbishment. It enables quantitative comparison of how this risk may be reduced by various remedial measures, e.g. installation of insulation, efficient heating systems and mechanical ventilation. The approach highlights the necessity for dwellings to be appropriate to the needs of occupants; dwelling insulation and heating systems must allow comfort conditions and space heating fuel bills which the occupants can afford. The result of insufficient heating is that people endure reduced temperatures which may lead to mould growth, condensation and building fabric decay. The use of this model will help to identify failures in design (e.g. inappropriate draught-stripping) and so avoid costly maintenance of remedies.

Developments of this condensation risk model has been led by demand. The imperative of providing an easy-to-use design tool has resulted in a simplified approach which has several shortcomings and unvalidated assumptions. Work is in progress to appraise the assumptions and to validate the model against real data and experience. Two main areas of concern are the use of average MIRH and ventilation analysis.

The assessment of condensation risk by using temperature and moisture generation averaged over time and space within a dwelling may not be entirely appropriate. Time averaged MIRH may be sufficiently low to regard a dwelling as theoretically free from condensation, yet condensation may occur at troughs of temperature and at peaks of moisture generation. In addition, thermal and moisture capacity of the building fabric is neglected in the above model but intermittent heating and occupancy may result in condensation. Similarly, spatial averaging does not account for high condensation risk in specific rooms of a dwelling. Transient affects can not be fully accounted for until the response of mould growth to transient conditions is understood, this work is being carried out the Building Research Establishment.

Partitioning of the dwelling into zones, as effected by BREDEM, may not give sufficient resolution for predicting condensation risk. However, analysis of air and moisture exchange between the two zones and to outside is complex. In the above model it has been assumed that the two zones are decoupled for moisture migration. Allowing for inter-zone moisture transfer can alter the Zone MIRH by up to 5%. Improving this part of the model will depend on the development of an appropriate ventilation model requiring relatively simple dwelling and occupant data. Similarly, the efficiency of extract fans in reducing internal vapour pressure (under both humidistat and occupant control regimes) needs elucidation.

The predictions obtained from any model are only as good as the input data. The above model has therefore been tested to see how sensitive the predictions are to the accuracy of the input data. The model is most sensitive to the fabric loss where a 1% change in fabric loss can result in a 1% change in predicted RH.

Preliminary comparisons between modelled results and measurements in several dwellings has shown good agreement when predicting the average dwelling MIRH (i.e. modelled MIRH within 5% of measured). The Zonal predictions however have been in error by up to 8% suggesting that the model does not adequately account for moisture movement between zones or the allocation of moisture production to each zone.

The condensation risk model discussed in this paper, now called 'Condensation Targeter', has been integrated into a commercial computer package called 'Energy Targeter'(14). Energy Targeter calculates the total energy cost, and total cost of remedial measures, as well as assessing the risk of surface and interstitial condensation. The integration of condensation assessment into a general refurbishment tool has meant that building designers who would not normally consider the quality of the indoor environment are made aware of condensation risks. Energy Targeter has therefore proved a useful vehicle for carrying research results into practice.

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