Some basic insight about the cost optimal opaque thermal insulation in buildings without overheating or cooling (e.g. transalpine Europe)

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Abstract

In the pursuit of nearly zero energy buildings, it appears a widely held belief that technological progress and cost reductions due to large-scale application will allow to achieve in an economic manner new buildings (or new building elements) with an extremely low energy demand (similar to so-called passive houses). This often results in very ambitious roadmaps, including scenarios for deep renovation of the building stock.

This hypothesis seems to materialize for major aspects such as heat generators (highly efficient condensing boilers), efficient ventilation systems and good envelope air tightness. However, cost optimal calculations performed in all EU member states usually result in economic thermal transmittances much higher than those typically found in passive houses (e.g. by a factor of 2).

The paper first derives the simple analytical formulas that provide a clear understanding of the different factors that influence the cost optimal insulation thickness. They are applicable to buildings that are not subject to meaningful overheating and/or do not need active cooling (such as most dwellings in transalpine Europe). They can be useful for setting requirements in public regulations.

The paper then illustrates in a graphical manner the influence on the economic optimum of several variables, such as the initial minimum cost of insulation, the marginal cost of extra thickness, the energy price and the upgrading of an already semi-insulated component. Among other things, the analysis shows that when components are (initially or during renovation) insulated, the full cost optimal insulation level should be achieved at once, because later retrofitting of suboptimal insulation usually becomes uneconomical.

Finally, the paper illustrates that it seems unlikely that typical passive house insulation levels will ever be effective from a strictly economic point of view, even if energy prices were to double or triple compared to current levels.

Introduction

It is clear that economic calculations of the optimal thermal insulation of building elements must have been done since a very long time. Certainly since the first oil crisis in 1973 and the ensuing higher energy prices, intensive analyses have been performed, also by public authorities with the purpose of defining in public regulations insulation requirements concerning both new construction and renovation. In the early years, relatively simple analyses were probably done, likely focussing on the thermal insulation only. With the rapid spread of computers and ever more sophisticated building calculation models, more accurate analyses could be performed, also including all other aspects that influence the final energy consumption (HVAC systems, envelope airtightness, lighting, etc.). The inclusion of the integrated energy performance into the public regulations, as epitomized by the EPBD, has also shifted the economic evaluations for public requirements towards the overall energy performance. The cost optimal thermal insulation requirements are then usually a side-result of such overall analysis. However, the overall analysis is also more of a black box, and it appears that in the process some explicit understanding with respect to the mechanisms that govern and limit cost optimal thermal insulation has been lost among the (younger generations of) all parties involved in the policy making process (including external stakeholders). As a result, also some unrealistic expectations with respect to the economic potential of thermal insulation may have become commonplace among policy makers. The insights gained from the simple but transparent analysis in this paper may contribute to robust national definitions of the nearly zero energy buildings, as stipulated in the EPBD.

This paper makes some simple deductions that again provide some basic analytical and graphical insight with respect to the cost optimal thermal insulation of opaque components in heating dominated climates, such as in middle and northern Europe. It concerns both completely new thermal envelope elements (in new buildings, extensions or full component replacements) and a posteriori insulation of existing thermal envelope elements.

The model is the degree-day method based on the average heating set-point temperature. It is well known that this approach (when including the total ventilation losses) overestimates the total heating energy use, notably because it neglects the internal and solar heat gains. However, as will be shown below, it can be used as a reasonably accurate approximation (also considering all the other uncertainties that intervene in the analysis) of the marginal energy savings when varying the insulation thickness.

Detailed, full building EPB calculations, or dynamic simulations, can certainly provide a more accurate analysis of the cost optimality, taking better into account the complex interactions that may exist between all factors that determine the final energy consumption, including the precise effects of internal gains. However, because these calculations are more of a black box, they provide less insight into the structural economic limitations towards ever better opaque insulation. The simple analytical and graphical analysis of this paper provides a more transparent understanding that can elucidate the policy debate; The model of the paper canbe used for estimating the optimal insulation value in a general manner (not limited to the particularities of individual projects), e.g. for getting an initial idea of what could be economic requirements in public regulations.

Note. In the reasoning of this paper it is assumed that in moderate summer climates such as in middle and northern Europe any potentially net negative effect of more thermal insulation on the cooling energy needs or on the risk of overheating can be sufficiently compensated for by additional intensive ventilation. See Annex 1 for a further discussion. Under this condition, the economic optimisation of the insulation thickness can thus be based on a winter analysis only.

The main structure of the paper is as follows:

- Firstly, the analytical derivation of the simple degree day model is remade, discussing in an abstract manner in detail its assumptions, approximations and limitations.
- Secondly, the insights that the model provides on several aspects of cost optimal thermal insulation are graphically illustrated.
- Thirdly, some quantitative numeric examples show the dependence of the optimal insulation level on energy and insulation costs and make the comparison with passive house insulation levels.

First approximation: without gains

In a first instance the compensating effect of (internal and solar) gains on the transmission (and ventilation) losses is neglected. This influence is further discussed later on in the paper.

In Figure 1, the thermal resistance of an opaque thermal envelope element (e.g. a wall or a roof) is shown on the x-axis. R_b is the basic resistance of the component before any insulation is applied, e.g. the resistance of an empty cavity wall or of a roof without insulation material when it concerns a new (or replaced) component, or the resistance of the existing component in the case of renovation (including the insulation that is already present, if any). When a layer of insulation of increasing thickness is added to the basic element, its total resistance increases linearly with the thickness of the insulation layer (assuming that the basic composition of the element remains unchanged, e.g. air layer of constant thickness in the cavity wall).

As the thickness of the insulation layer increases, so will the initial investment costs. See Annex 2 for a basic exploration of potential cost components. This is shown by the line f_1 (function 1) in Figure 1. (The rising line may take a somewhat other shape than a straight line, e.g. slightly curved with slightly decreasing slope, to reflect slightly reducing marginal costs with increasing thickness.)

In stationary conditions, the instantaneous heat flux through the component is proportional to its thermal transmittance (U) and the temperature difference between in- and outside:

$$q = U \cdot \left(\theta_{int} - \theta_e\right)$$

where

- q instantaneous heat flux [W]
- U the thermal transmittance of the component [W/m²K]
- θ_{int} the internal temperature [°C]
- θ_e the external temperature [°C]

If there would be no gains in the building, the internal temperature would never rise above the set-point for as long as the external temperature is lower. Whenever the external temperature becomes higher, there will be an inward heat flux. Depending on the thermal mass (of the component itself and of the overall internal fabric of the building), such inward flows can compensate outwards flows at later times. In most buildings with a minimum of thermal mass this is probably to a very large extent true on a daily basis (day-night cycle: inward flow during the day accumulates heat in the fabric, which covers (part of) the outward flow at night). This effect probably extends to a lesser extent over several days (warm "weeks" alternating with colder "weeks"), but it does not contribute to seasonal variations, transferring surplus summer heat to cover winter losses.

When integrating above equation over a full year in order to obtain the net annual outward heat flow that needs to be compensated by the heating system, it therefore appears that an evaluation of the average outdoor temperature on a monthly basis may be the most appropriate approach, maybe slightly on the conservative side (i.e. somewhat underestimating the total heating needs caused by the component[1]). The annual transmission flow is then given by

$$Q_a = U \cdot \sum_m \left[(\theta_{int,set,H} - \theta_{e,m}) \cdot t_m \right]$$

$$= \frac{1}{R} \cdot \sum_m \left[(\theta_{int,set,H} - \theta_{e,m}) \cdot t_m \right]$$

where
- Q_a the annual transmission flow [MJ]
- U the thermal transmittance of the component [W/m²K]
- $\theta_{int,set,H}$ the average set-point temperature for heating [°C]
- $\theta_{e,m}$ the mean external temperature of month m [°C]
- t_m the duration of month m [Ms]
- R the thermal resistance of the component [m²K/W]

The equation is summed over all months m with a mean outdoor temperature lower than the average set-point temperature.

Dividing this annual heat flow by the average overall heating system efficiency[2] gives the annual consumption of delivered energy. With hypotheses about the future evolution of the energy costs and about discount rates, the net present energy cost (NPEC) of the consumption over the lifetime of the envelope component can be estimated.

$$f_2 = NPEC = \frac{Q_a}{\eta_{sys}} \cdot C \cdot PWF$$

with

$$PWF = \sum_{j=1}^{N} \frac{(1+i)^{j-1}}{(1+d)^j}$$

$$= \begin{cases} \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] & \text{if } i \neq d \\ \frac{N}{1+i} & \text{if } i = d \end{cases}$$

where
- NPEC the net present energy cost [euro]
- Q_a the annual transmission flow [MJ]
- η_{sys} the overall heating system efficiency [–]
- C the cost of the heating energy carrier at the end of the first time period [euro/MJ]
- PWF the present worth factor[3] of the heating energy carrier [–]
- i the cost inflation rate per time period of the heating energy carrier [–]
- d the discount rate per time period [–]
- N the number of time periods of the economic evaluation [–], e.g. 20 or 30 years

1. But see later on in the paper for the much larger impact of the gains.

2. Taking into account all the losses of production, storage – if any –, distribution and emission.

3. The PWF allows to calculate the net present value for a given discount rate of a regularly recurring future monetary flow that is subject to a fixed inflation rate. In this instance the flow concerns the annual fuel bill. Cf. basic economics handbooks or e.g. "Solar engineering of thermal processes" J.A. Duffie, W.A. Beckman, 2006, chapter 11.5, or http://www.financeformulas.net/Present_Value_of_Growing_Annuity.html with there symbols r and g instead of d and i here in this paper.

Above formula for the PWF is for a fixed fuel inflation rate. It goes without saying that if a different future energy cost scenario is considered (e.g. a fluctuating one), the present worth factor can of course also easily be calculated by discounting the (varying) annual costs year by year.

The expression for the net present energy cost can be rewritten as

$$f_2 = NPEC = \frac{\alpha}{R} = \alpha \cdot U$$

$$\text{with } \alpha = \frac{\sum_m \left[(\theta_{int,set,H} - \theta_{e,m}) \cdot t_m \right]}{\eta_{sys}} \cdot C \cdot PWF$$

It is thus clear that the NPEC is inversely proportional to the resistance of the envelope element. This is shown by the curve f_2 (function 2) in Figure 1.

Assuming that there are no extra maintenance or other operational costs (other than energy) related to the extra insulation, the total life cycle cost (LCC) is the sum of the initial investment cost (f_1) and the net present energy cost (f_2). This is shown by curve f_3 (function 3) in Figure 1.

$$f_3 = f_1 + f_2$$

At the lowest point (i.e. lowest cost) of the LCC f_3 curve, the derivative is zero.

$$\frac{df_3}{dR} = 0 \Rightarrow \frac{df_1}{dR} = -\frac{df_2}{dR}$$

The cost-optimal resistance thus corresponds to the point where the downward slope of f_2 is equal to the upward slope of f_1. From this optimal resistance, the optimal insulation layer thickness can readily be determined.

With respect to the features of the initial cost curve (f_1), the following observations can be made:

- The optimal resistance is independent of the value of the basic resistance R_b.
- It is also independent of the initial stepwise cost (at R_b) associated with starting to apply insulation.
- The optimum only depends on the marginal cost (including secondary costs) of extra resistance (local slope of f_1).

The last observation implies that if the marginal insulation cost for different types of envelope elements (e.g. roofs and walls) would be (more or less) the same (e.g. primarily determined by the insulation material cost itself), then the optimal insulation value will also be (more or less) the same.

For an existing structure the last observation also implies that if some insulation is already present, the optimal resistance of a posteriori insulation will be identical to that of an otherwise identical structure without any initial insulation or to that of a completely new structure (if the same insulation technology and costs apply).

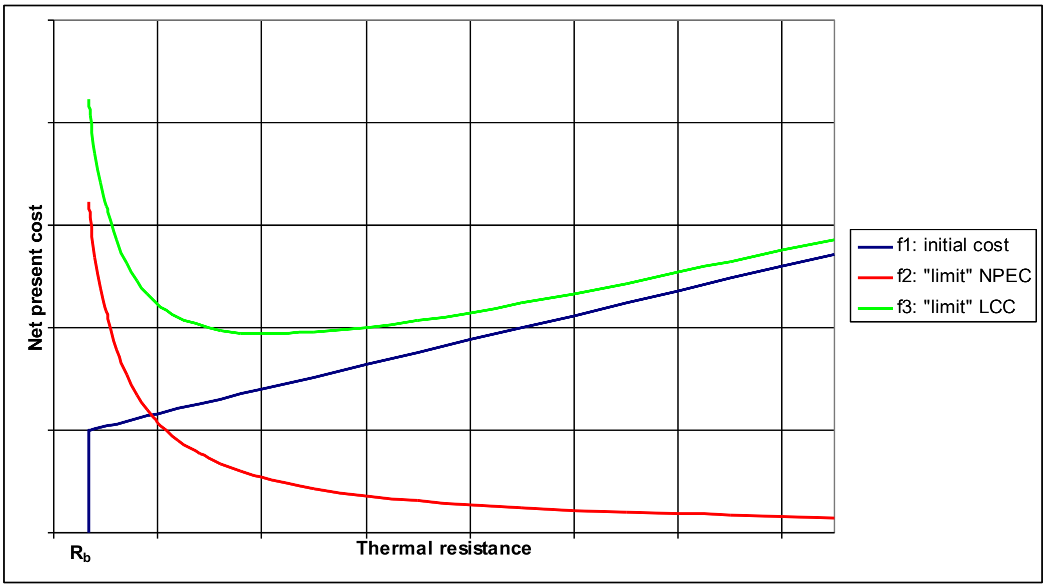

Figure 1 Different cost components as a function of the thermal resistance.

The observations above are further illustrated by means of some graphs later on in the paper. But first see the clause on the effect of the internal and solar gains, which has been integrated in the graphs later on.

Dependencies

CLIMATE

If in good approximation it can be assumed that the cost of the insulation varies linearly with its resistance (as was already shown graphically in Figure 1), the initial investment cost can be written as:

$$f_1 = c_1 + c_2(R - R_b)$$

and thus

$$\frac{df_1}{dR} = c_2 \quad \text{and} \quad \frac{df_2}{dR} = -\frac{\alpha}{R^2}$$

$$R_{opt} = \sqrt{\frac{\alpha}{c_2}} \propto \sqrt{DD}$$

where

c_1 the initial incremental investment cost at R_b [euro]

c_2 the marginal cost to add an extra unit of resistance [euro/(m²K/W)]

DD the degree days [Kdays], i.e.

$$\sum_m \left[(\theta_{int,set,H} - \theta_{e,m}) \cdot t_m\right] / 0.0864$$

It can thus be seen that for a given heating system and fuel price scenario the optimal resistance does not increase linearly with the "severity of the winter" (heating degree days) but only proportionally with its square root, i.e. if the winter is "twice as cold" in one location compared to another (i.e. there are 2 times as many heating degree days), then the optimal resistance doesn't increase with a factor of 2, but only with the square root of 2, i.e. with 41 %.

UNHEATED SPACES

An example of an unheated space is an attic outside the thermal envelope. As above, the analysis is made supposing there are no (solar and internal) gains.

The temperature difference between the inside and the unheated space can by convention be expressed as a fraction of the difference between in- and outside temperatures, symbol b_U, which varies[4] between 0 and 1 (if no gains):

$$b_U = \frac{(\theta_{int} - \theta_U)}{(\theta_{int} - \theta_e)}$$

where

θ_{int} the internal temperature [°C]

θ_U the temperature of the unheated space [°C]

θ_e the external temperature [°C]

Replacing the monthly external temperature $\theta_{e,m}$ by the monthly temperature of the unheated space $\theta_{U,m}$ in the equation for the NPEC above and then introducing the factor b_U, ultimately leads to

$$f_4 = NPEC_U$$

$$= \frac{1}{R} \frac{\sum_m \left[b_U \cdot (\theta_{int,set,H} - \theta_{e,m}) \cdot t_m\right]}{\eta_{sys}} \cdot C \cdot PWF$$

$$= \frac{b_U \cdot \alpha}{R}$$

and thus

$$\frac{df_4}{dR} = -\frac{b_U \cdot \alpha}{R^2} \quad \text{and} \quad R_{opt,U} = \sqrt{\frac{b_U \cdot \alpha}{c_2}}$$

4. The better the unheated space is insulated, the lower the b-factor is. The b-factor can be calculated from the overall heat transfer coefficients between the indoors and the unheated space, and between the unheated space and the outdoors.

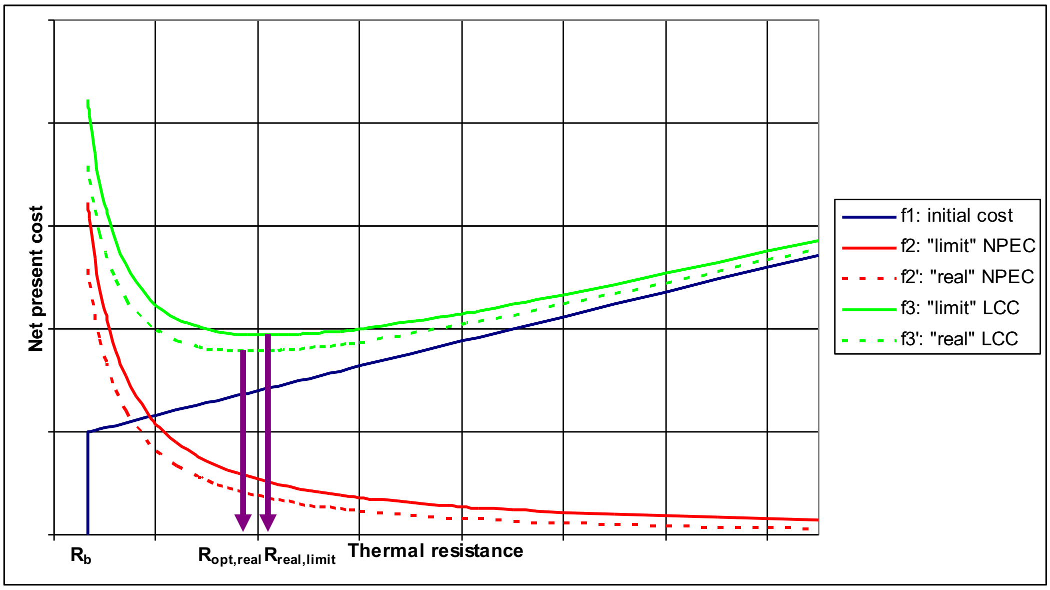

Figure 2 Influence of the gains on the energy cost and on the total cost (dotted lines).

The reduction of the temperature difference across the wall that is caused by the unheated space, self-evidently has the same effect as a variation of the outside climate (cf. above). The optimal resistance thus doesn't decrease linearly with smaller b-factor but only proportional with the square root of the b-factor. As many unheated spaces (attics, single glazed sunspaces, etc.) are often not well insulated and not very airtight, and thus have a b_U-factor close to 1, the difference between both (i.e. between b and square root of b) is then rather small, and the impact on the cost optimal resistance thus limited.

Influence of the gains

Internal and solar gains provide a "free"[5] source of heat that to a greater or lesser extent compensate the heat losses, reducing the amount of heat that needs to be supplied by the heating system. The annual energy cost associated with a transmission heat loss as calculated above is thus in principle an overestimation of the real energy cost. The exact contribution of the gains to the transmission heat loss of a given component is not easily determined. For one thing, the size of the internal gains is difficult to predict since it largely depends on individual user behaviour, which is very variable. For another thing, the heat gains can compensate for all the (transmission and ventilation) heat losses of a room or thermal zone. An overall thermal energy balance thus needs to be made on a case by case basis in order to assess the exact impact on improving the thermal insulation of a single component.

If in an existing building with large overall transmission and ventilation losses[6], the thermal insulation of a single component is improved, the heat gains to a large extent can usefully "redirect" towards the remaining heat losses. Initial reduction of the thermal losses will thus still result in an energy saving close to the one calculated according to the formulas above. This is to a certain extent still true in new construction, unless the overall losses (including hygienic ventilation losses and in/exfiltration) are very strongly reduced (tending towards passive house standard) so that the gains outweigh the overall thermal losses during an ever larger fraction of the year.

Figure 2 shows in a schematic manner the influence of the gains on the heating energy cost associated with the transmission losses through a given component. The dotted line f_2' lies to a greater or lesser extent below the curve f_2 as defined in Figure 1. The exact course[7] depends on all the remaining losses in the given building and on the amount of gains. However, as a matter of principle, it can be said that the slope of the dotted curve is for any given R-value somewhat less downward than the original curve f_2. This is caused by the slow reduction of the usefulness of the overall gains with increasing resistance of the component. As R tends towards infinity, both f_2 and f_2' converge towards zero. The point where the derivative of f2' is equal to the negative of the cost curve ($-c_2$), i.e. the point of the economic optimum, slightly shifts to the left, i.e. corresponding to a somewhat smaller insulation thickness.

This is also immediately obvious in the total cost curve f_3'. However, generally speaking this effect is not very large: the new total cost is visibly lower than the old one, but the optimal resistance is not much smaller (i.e. to the left in the graph) than the one obtained with the formulas above. This is because the useful gains only diminish very slowly with in-

5. Part of the internal gains are due to the electricity consumption of all sorts of electric devices and thus have already been a cost of energy. High electrical internal gains are thus not "free" but constitute a substantial energy cost. The cost per unit heat produced of electric internal gains is usually higher than the same amount of heat delivered by the heating system (unless electric resistance heating is used).

6. This means: with initially little or no thermal insulation, not especially airtight, etc.

7. For a given, practical case, the exact shape for a specific component could in principle be calculated by making overall heat balances of the building. First, the loss of the component to be insulated is set equal to zero (i.e. U=0 and R=∞). Next, the calculation is redone for different, discrete, finite values of the resistance of the component, down to R_b. The increase of the total heating energy cost (for the building as a whole) compared to the first case (i.e. for U=0 and R=∞) defines the exact curve.

creasing insulation. (If the useful gains would be constant, i.e. independent of the thermal resistance, the curve f_3' would simply move vertically downward and the optimal resistance wouldn't vary at all).

Smaller heating system

A carefully sized heating system can become smaller as the insulation improves. A downsized heating system represents a reduction of the initial investment cost which may warrant some extra insulation. However, in many instances the cost of basic heat emitters (e.g. standard radiators) is not high to start with, and so their potential cost reduction is also limited. In new, fairly energy efficient dwellings in maritime Western Europe with a mild winter climate, the size of the heat generator (boiler or heat pump, etc.) is often determined by the hot water requirements (as space heating and domestic hot water are often supplied by the same apparatus). This is especially true for instantaneous, flow-through water heaters. In these instances, the size of the generator can thus not be reduced, even if the space heating requirements by themselves would allow for a smaller generator. In general, the impact of the heating system cost reductions on an improved insulation can therefore be expected to be very small – or often even negligible – in most new constructions. In renovations of buildings with initially a large heat loss coefficient, the financial benefit may be somewhat larger (in as far as the existing heating system is also being replaced and in as far as the effect of the improved insulation is properly taken into account in the sizing of the boiler).

For the sake of completeness, the principle influence on the initial and total cost functions is still described in the footnote[8], but the actual quantitative impact may usually prove without consequence on the optimal insulation resistance.

In buildings with an extremely low overall heat loss coefficient (passive house standard or comparable), the heat emission elements are sometimes omitted altogether, with (the small quantities of required) heat being distributed only by post heating of the mechanical ventilation supply air. Such complete elimination of a conventional heat emission system normally constitutes a sudden, discontinuous cost reduction, which may to a certain extent compensate for the extra cost of the advanced insulation and of the other heating needs reducing measures (namely triple glazing, an airtight envelope and mechanical heat recovery ventilation). To what extent both cost effects balance out, and whether with such approach sufficient thermal comfort can be guaranteed at all times, even under the harshest winter conditions, is the object of controversy among proponents and antagonists of such solution.

8. The marginal cost of the heating system caused by a m^2 of an envelope component is inversely proportional to its thermal resistance. As the resistance tends towards infinity (R=∞, i.e. U=0), there is no heat loss any more through the component, and no heat emission and generation power are needed; the marginal extra heating system cost thus tends towards zero. As the resistance is reduced, the extra cost of the heating system increases. In the graphs of the previous part, this cost is a (very low lying) hyperbola. This cost needs to be added to the initial cost of the insulation to obtain an overall initial cost, which will thus become somewhat higher, especially towards low resistances. The slope of the curve thus becomes slightly lower, shifting the balance point with the decreasing net present energy cost towards a somewhat higher resistance. Or equivalent, the minimum of the total life cycle cost occurs at a somewhat higher resistance. The effect of a smaller heating system thus goes in a direction opposite to the effect of the gains (lower optimal resistance).

Graphical illustrations

The Figures 3 to 7 are of a qualitative nature and serve to illustrate the principles. No quantitative conclusions can be drawn from them. Quantitative evaluations should be recalculated with an appropriate set of numerical hypotheses (climate, investment costs, energy price scenario, etc.) for any specific case. As an illustration, some quantitative examples are given in Figures 8 to 10.

INFLUENCE OF THE BASIC RESISTANCE OF THE COMPONENT

Figure 3 shows 2 cases: A and B. The resistance of the uninsulated component (R_b) is much lower in case A than B (e.g. a massive external wall and a – modestly – insulated cavity wall). Applying external insulation to each of them entails an identical initial cost c1, and then an identical increase as the insulation thickness increases, resulting in 2 parallel lines for the initial cost curves f_1. The net present energy cost curves (f_2') are of course identical and only depend on the total resistance. Since the slopes of both initial investment curves are identical and the energy cost curves are the same, the point of equal derivatives is identical for both cases, as can also readily been seen in the overall cost curves: although the curve f3' for case A is slightly higher than for case B, both curves are parallel and their minima occur at the same resistance. **So, the graph illustrates that the initial basic resistance (R_b) does not influence the optimal final resistance.**

INFLUENCE OF THE INITIAL MINIMUM COST OF APPLYING INSULATION

Figure 4 shows again 2 cases. Now the difference is the starting cost of applying insulation (c_1). In case B, it is 2 times larger than in case A. This moves the investment cost curve (f_1) up by a constant amount, but does not influence its slope. The energy cost curves (f_2') are of course again identical in both cases. Thus the point of equal derivatives remains identical, as can also readily be seen in the overall cost curves: although the curve f_3' for case B is displaced upward by a constant amount compared to case A, the minima occur at the same resistance. **So, the graph illustrates that the initial starting cost of applying insulation does not influence the optimal final resistance.**

INFLUENCE OF THE MARGINAL COST OF EXTRA INSULATION

Figure 5 shows again 2 cases. Now the difference is the marginal cost of increasing the insulation (c_2), which in the context of this paper is the additional cost to add a unit of thermal resistance (see above). It is the slope of the initial cost curve (f_1) in Figure 5. In the example, it is 1.5 times larger in case B than A. The energy cost curves (f_2') are of course again identical in both cases. As the slope of the investment curve is much steeper in case B, the tangent to the energy curve moves towards lower resistances. This is also readily seen in the overall cost curves (f_3') where the minimum shifts to the left. **So, the graph illustrates that the marginal insulation cost affects the optimal resistance strongly.**

INFLUENCE OF THE ENERGY PRICE

In Figure 6 the energy cost of case A is 3 times lower than that of case B[9]. The curve f_2' is thus 3 times lower in case A compared to case B. The point where the derivative equals the slope

9. Taking general inflation into account, this ratio corresponds roughly to the heating oil prices in the period from the late eighties to the early nillies, compared to the prices in the period 2011–2014 (when crude oil prices were most of the time above 100 USD/barrel).

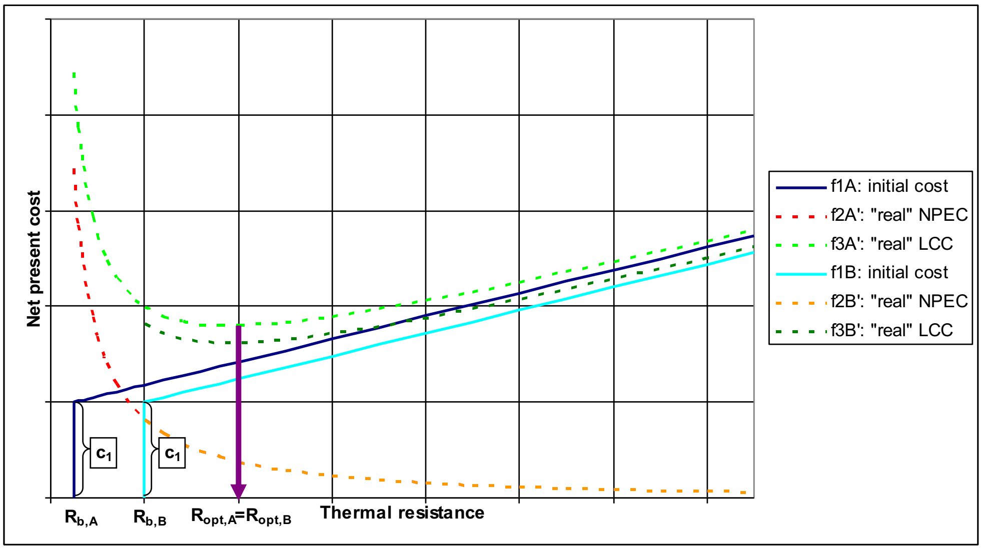

Figure 3. Influence of the basic resistance of a component on the cost optimal resistance.

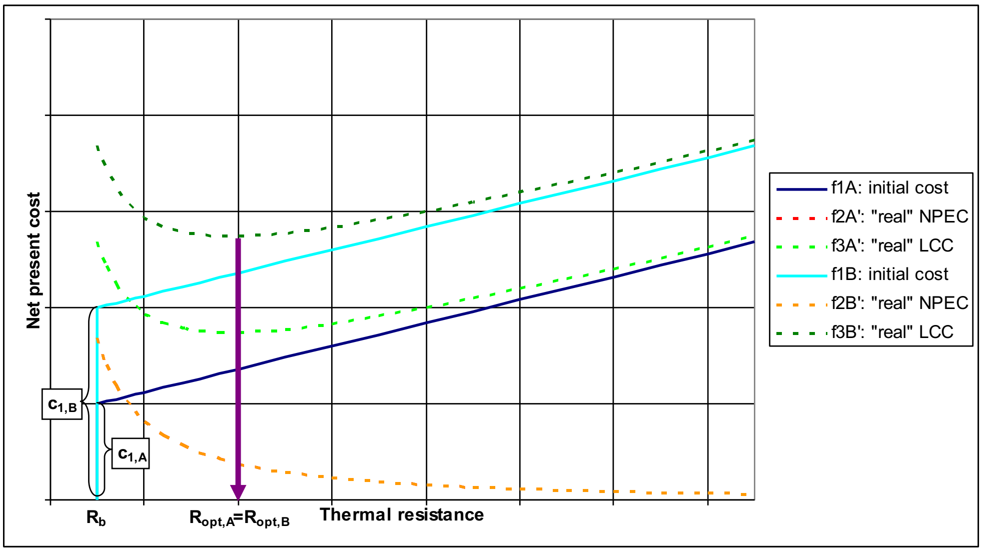

Figure 4. Influence of the starting cost of applying insulation on the cost optimal resistance.

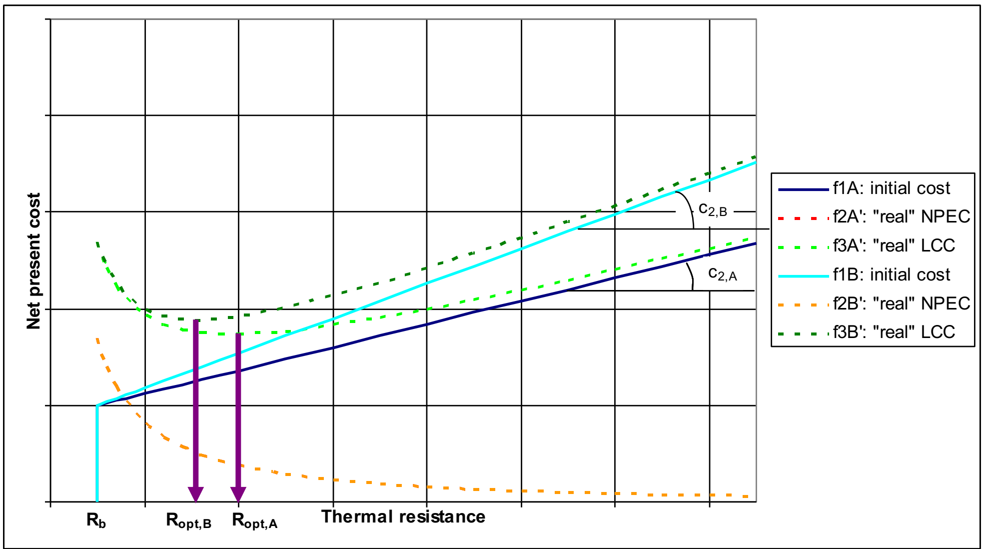

Figure 5. Influence of the marginal cost of extra insulation on the cost optimal resistance.

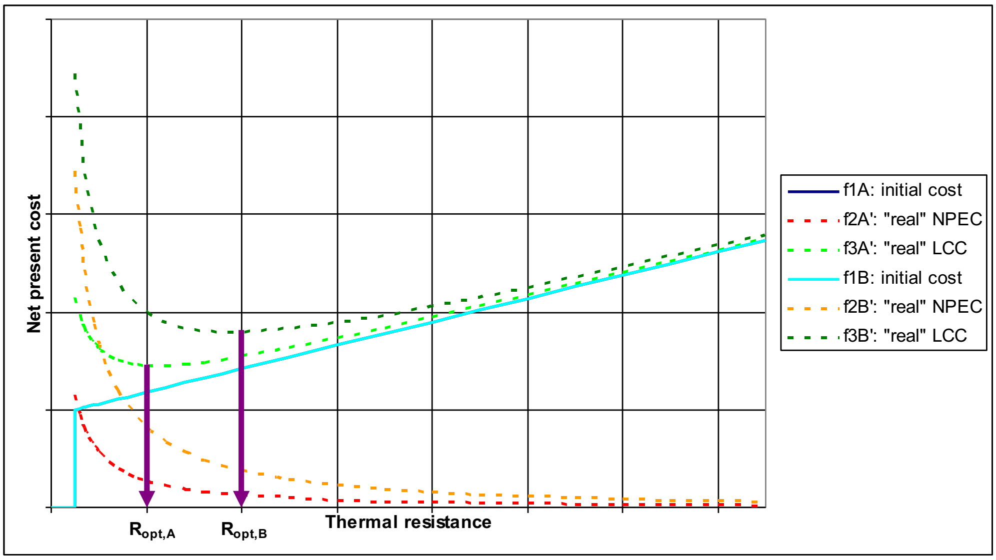

Figure 6. Influence of the energy price on the cost optimal resistance.

of the investment curve thus shifts towards a lower resistance. This lower optimum can also readily be seen in the total cost curve (f_3'). It is clear that founding such long term decisions as the insulation of the thermal envelope on volatile energy prices of the day has far reaching consequences.

UPGRADING OF A MODERATELY INSULATED COMPONENT

Figure 7 shows a component that was insulated according to the cost optimum at a time when the energy cost was 3 times lower than in a recent period of high prices (e.g. new construction in the mid 1990s in Belgium, when heating oil prices were below 0.30 Euro/litre, compared 0.90 Euro/litre at its peak in 2011–2014): curves A and $R_{opt,A}$ in the graph. This is the starting point for the new situation B ($R_{b,B}$). In a scenario where the high energy prices of 2011-2014 would have persisted long into the future, the present value of the future energy costs are given by point 1 (circle at the beginning of the dotted line f_{2B}'). When in this situation the installation of additional insulation would be considered, the corresponding investment curve[10] is given by f_{1B}, leading to the total cost curve f_{3B}'. The optimal resistance of the component with additional insulation is the same as for today's new construction (see the analysis earlier in the paper and the example in Figure 6). However, the total cost (sum of the energy cost and the cost of applying the extra insulation) is point 2 (also circled). This corresponds to a much higher net present cost than point 1. So, even when it would be technically and practically feasible to add insulation, in this situation not insulating is cheaper than doing the extra investment[11], since even at the most favourable point, the additional savings cannot compensate for the extra investment cost.

As can be seen, in this example the new optimal resistance ($R_{opt,B}$) would be twice the initial one ($R_{opt,A}$). This means that the energy consumption would only be half the present one if the component would from the start have been insulated according to present energy prices. In view of the multiple fundamental energy issues that society needs to tackle, this is of course a lost opportunity.

Quantitative examples

In this paragraph the simple mathematical degree-day model, which was derived above, is applied to a couple of practical cases. It concerns the limiting values, not yet taking into account the effect of gains (see above); the curves thus constitute a bit of a too favourable result (in the sense of overestimating the optimal thermal insulation). Unless otherwise specified for each of the variations below, the following numeric values have been used:

- DD = 2813 Kdays (i.e. for Brussels climate at an average indoor set-point temperature of 18 °C; yearly average outdoor temperature 10.26 °C).
- η_{sys} = 0.85, which is considered representative for the overall heating system efficiency in new construction.
- PWF = 20, which corresponds (rounding upwards) to an energy inflation rate i of 2 %, a discount rate d of 5 % and a time period of 30 years[12].
- fuel cost = 7 eurocents/kWh gross calorific value (GCV)

Figure 8 shows how the optimal thermal transmittance (declining curves) and resistances (rising curves) vary as a function

10. The assumption is made that the marginal cost of the extra insulation (c_2) is the same for the renovation as for new construction, as both costs are usually mainly determined by the material. In some instances the starting cost c1 may actually be larger in the case of renovation (case B), since for new construction (case A) some finishing work needs to be done anyway, whether insulation is applied or not. So, in new construction this then doesn't constitute an extra cost related to the application of insulation. On the other hand, if in the case of thermally upgrading an existing component, some renovation work is done anyway for other raisons (e.g. repainting or rerendering of the exterior of a facade), then this cost can (fully or partly) be deducted from c1 if insulation is applied at the same occasion. Obviously, not seizing the opportunity to insulate an existing component at the time of such other works, is a very important lost opportunity in economic terms.

11. But note that this conclusion of course strongly depends on the value of c_1. If the initial starting cost of extra insulation would be very low (close to zero), taking action might still pay for itself in this example.

12. Note that a PWF of 20 seems a relatively high value; in common economic analyses PWFs of 10 or even less seem more common.

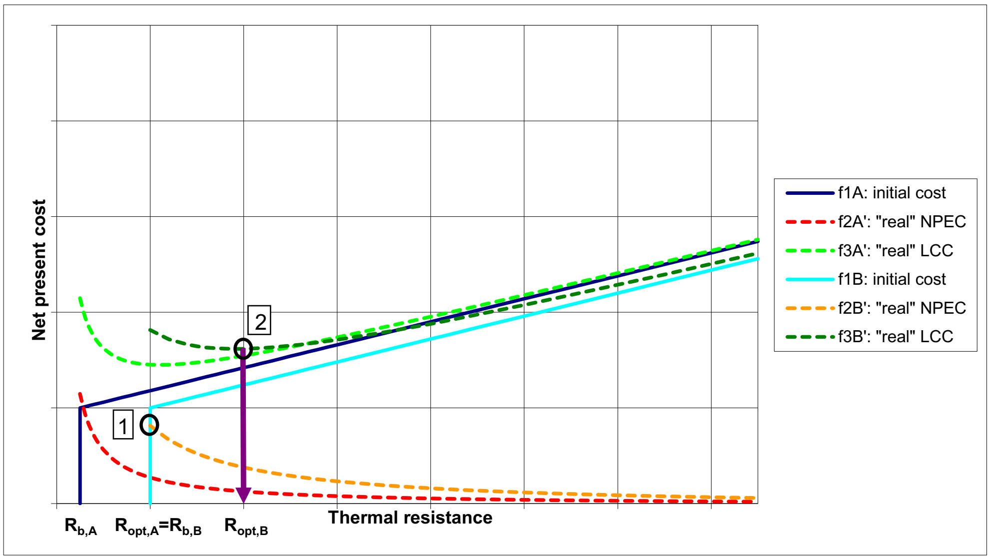

Figure 7. Further insulation of an already moderately insulated component.

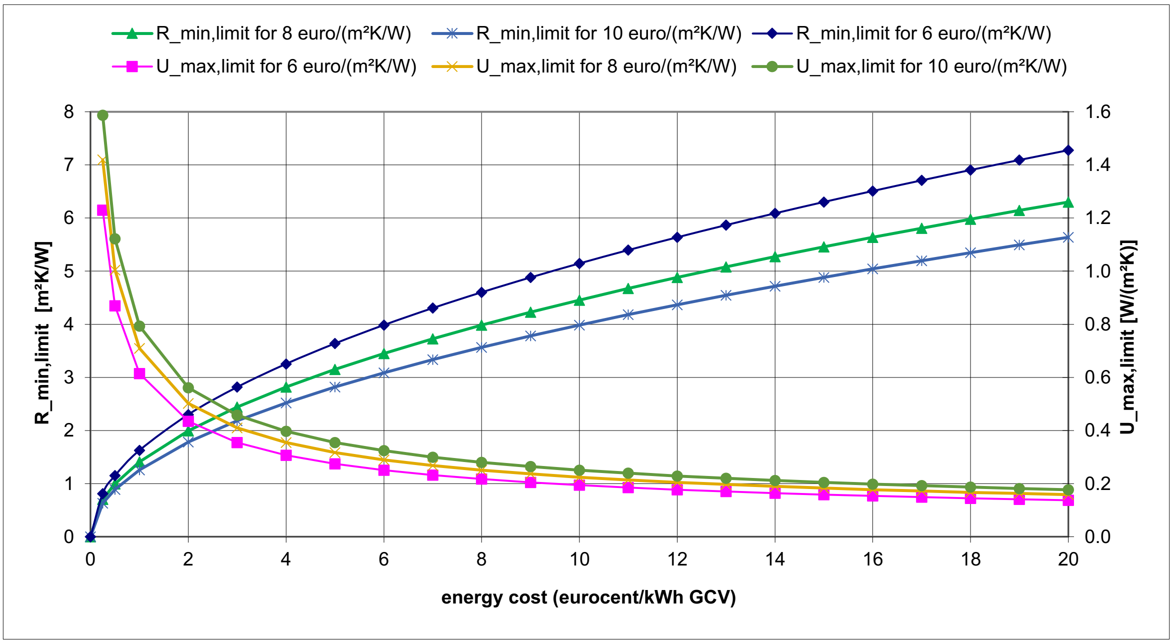

Figure 8. Thermal resistances and thermal transmittances as a function of the energy cost per unit gross calorific value (GCV).

of the energy price for three different marginal prices of the thermal insulation, namely c_2 = 6, 8 and 10 éuro/(m²K/W). The typical marginal costs vary depending on the type of component (floors, walls, flat/sloped roofs, etc.) and this range of values appears typical for common components in Western Europe, as can be inferred from national cost optimal studies done in fulfilment of the EPBD obligation.

It can be seen that even if the natural gas costs were to increase with more than 50 % from 7 Eurocents/kWh (current prices in Brussels) to 11 eurocents/kWh[13], the optimal resistances would only increase from 3.3 to 4.2, from 3.7 to 4.7 and from 4.3 to 5.4 m²K/W, for c_2 equal to 10, 8 and 6 éuro/(m²K/W) respectively. This is still far away from the typical values of 8 to 10 m²K/W found in typical passive houses, which are not even reached at a still much higher energy cost of 20 Eurocents/kWh. As mentioned above, in passive houses the conventional heat emission system can often be omitted, resulting in a reduction of the initial investment cost. Since the cost of the heat emission system is in mild winter climates as maritime Western Europe relatively low, this effect appears insufficient to make (even in combination with the additional energy savings) the extra insulation cost effective[14].

13. This would correspond to the same financial bonus (in terms of primary energy saved) presently given to off-shore wind energy in Belgium, namely ~100 Euro/MWh electricity which converts with a conventional primary energy factor of 2.5 for electricity to 40 Euro/MWh or 4 eurocents/kWh fossil fuel saved. Due to substantial energy taxes a price level of around 11 eurocents/kWh natural gas for residential consumers seems to have been applicable in Denmark since many years.

14. See for instance: Verbeeck G., Hens H., Development through life cycle optimisation of extremely low energy and pollution dwellings. Part 4: evaluation and strategy, Jan. 2003–Dec. 2006

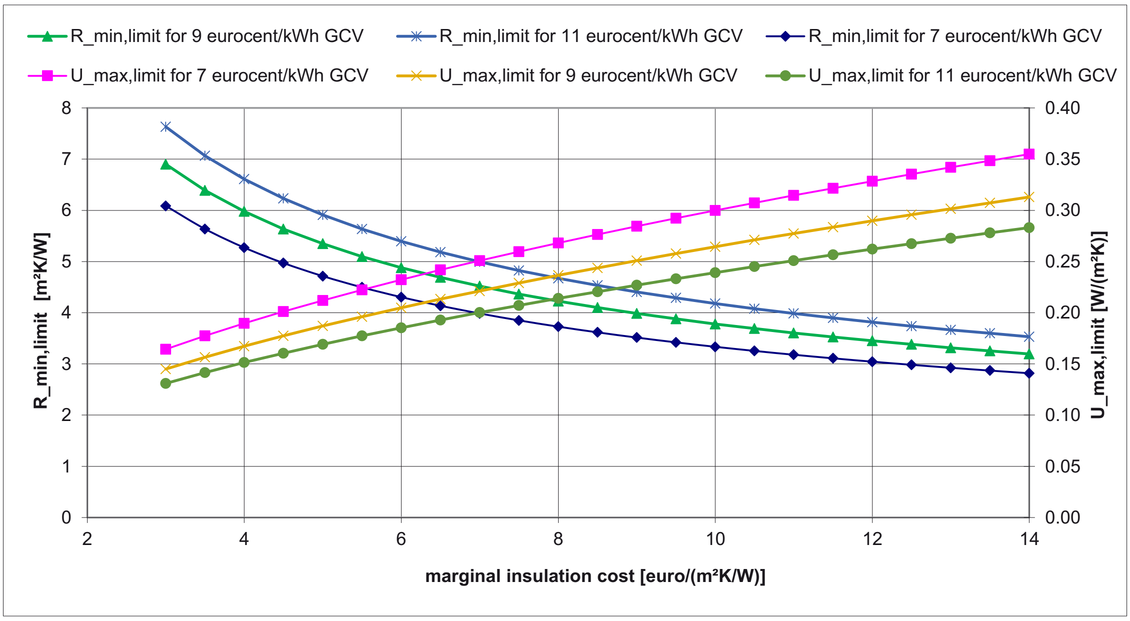

Figure 9. Thermal resistances and thermal transmittances as a function of the marginal insulation cost (c_2).

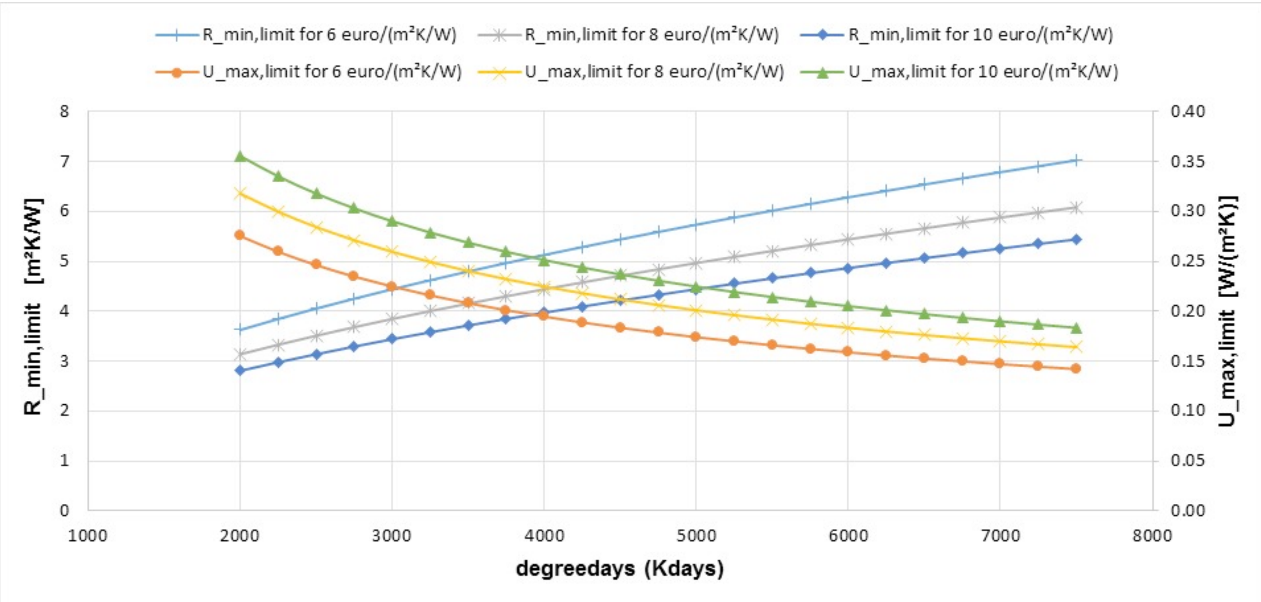

Figure 10. Thermal resistances and thermal transmittances as a function of the degreedays.

Figure 9 shows the results in a different manner: the optimal thermal transmittance (rising curves) and resistances (declining curves) as a function of the marginal insulation cost (parameter c_2). It can again be seen that the optimal thermal resistance stays even under the most favourable circumstances below the typical passive house resistance values of 8 m²K/W and more. Still, the graph shows that a reduction of the initial investment cost would result in improved insulation.

When new, innovative products come onto the market, their sales prices sometimes decrease rapidly as they find large scale application. However, thermal insulation is already a long-established, mature volume market. So, it is unclear whether significant cost reductions are still to be expected for traditional insulation materials, and thus whether this factor can still play a role of importance in an economic justification for better insulation. If new types of insulation material would show a rapidly declining and ultimately lower cost per thermal resistance, then the optima will of course shift towards better insulation levels.

Figure 10 shows the optimal thermal transmittance (declining curves) and resistances (rising curves) as a function of the degreedays for three different marginal prices of the thermal insulation. As shown analytically earlier in the paper, the optimal thermal resistance only rises proportional with the square root of the degreedays. In locations with a mild winter climate (e.g. less than 2000 Kdays), the curves should be considered with extra caution as in these locations in many instances the summer climate will be warmer too, and overheating or cooling are thus more prone to occur, so that the simple winter degreeday analysis of this paper can no longer be used as a basis for evaluation.

Conclusions

It has been shown that the simple degree-day method based on the average heating set-point temperature in most instances probably slightly overestimates the cost optimal resistance of opaque insulation because the useful gains are not constant but slowly decrease with increasing resistance.

Despite this limitation, the following conclusions can be drawn in good approximation, as has been shown in detail:

- The optimal resistance is independent of the value of the basic resistance R_b of an opaque building element (i.e. the resistance at starting point before any insulation is added).
- The optimum is also independent of the initial incremental cost associated with starting to apply insulation.
- The optimum mainly depends on the marginal cost (including secondary costs) of adding extra resistance.
- The optimum does not increase linearly with the severity of the climate, but proportionally with only the square root of the climate severity (expressed in terms of degree-days).
- For unheated adjacent spaces, the optimum doesn't decrease linearly with smaller b-factor (i.e. the temperature reduction factor) but proportionally with only the square root of the b-factor.
- The internal and solar gains shift the economically optimal resistance to a somewhat lower value, but generally speaking, the difference is probably small (unless the buildings would tend towards very low heating needs such as in passive houses or equivalent).

Several of these conclusions seem fairly well, but not universally, known in the construction sector. The derivation in the paper provides some analytical understanding.

Applying the model with representative numeric values shows that the levels of thermal insulation typically found in passive houses cannot be justified from a purely economic point of view, even if the energy prices were to double or triple[15]. This understanding may be useful for national definitions of "nearly zero energy buildings", as stipulated by the EPBD.

Annex 1: thermal insulation and summer comfort/cooling

In moderate summer climates, the daily average outdoor temperature in summer generally remains well below the upper thermal comfort limit. In this context the thermal insulation has a twofold effect. At the one hand, it reduces the inward heat flow of external surfaces that get hot because of the absorbed solar radiation (due to a strong solar exposure and a high absorption coefficient), for instance dark roofs. Also, during the – generally limited – time that the external temperature rises above the indoor temperature at the hottest hours of the day, the inward heat flow will be reduced. On the other hand, due to the relatively low daily/monthly average outdoor summer temperatures, the transmission flow is outward during a large fraction of the time and as a result contributes to evacuating the surplus heat gains and thus to reducing the risk of overheating or the cooling load. As the thermal insulation of the building envelope increases, heat gains are removed to an ever lesser extent by means of this transmission mechanism. In moderate summer climates, the second effect of lower outward heat flows may dominate over the first effect of reducing the inward heat flow, thus causing an overall increase of the cooling demand. However, this effect can be countered by increasing the outward heat flow by other means, notably by intensive ventilation, at any time when the outside air temperature is lower. (On hot days thus usually only during the night time.) For proper operation, the openings for intensive ventilation ideally provide a high degree of protection against the intrusion of insects, against burglary, against penetration of rain and other potential negative side effects. Effective systems for intensive ventilation may be room by room mechanical extraction (of the warmest air near the ceiling) directly to the outside, with external air entry through any other dedicated opening (duct through the wall, tilted window, concentric duct around the extraction, etc.)

Annex 2: total investment cost of insulation as a function of thickness

Obviously, the initial investment costs should include all extra expenses as the insulation layer becomes thicker, i.e. not only the extra cost of the insulation material itself, but also the cost of any extra labour, of secondary consequences, etc. In the case of cavity wall insulation for instance, the wall ties will need to get longer accordingly, the foundation may need to get wider, and – for constant internal dimensions, i.e. uncompromised useful net floor area – the outer leaf and the roof will need to be somewhat larger, etc. (If spatial constraints – whether physical or of a regulatory nature – do not allow to increase the external dimensions, the useful floor area will reduce. Whether this affects the property value of the building depends on the relative weight of 2 counteracting effects: at the one hand the value of the net floor area, on the other hand the value of improved energy performance of the building.)

Generally speaking, it can be assumed in good approximation that the initial investment cost will increase linearly with the insulation thickness (as shown in Figure 1, and further made explicit later on in the text). However, this hypothesis is not strictly needed in the initial, general deduction. Normally, there is a stepwise start of the cost when the switch is made from no insulation at all to installing a layer (initially of small thickness in the reasoning of this text). This initial increment may vary strongly depending on the type of component (wall, roof, etc.), the type of insulation (cavity, external, etc.), the cost of the external surface (type and cost of the brick of an outer leaf of a cavity wall, type of rendering of external insulation, etc.).

Sometimes there may also be a stepwise increase of the cost as a certain thermal resistance is reached, for instance when a switch to 2 layers must be made (e.g. because the maximal insulation thickness that is available on the local market is exceeded). As long as such step changes do not occur to the left of (and close to) the optimum, they do not change the optimum.

15. A holistic approach some years ago of the overall energy performance, including the technical building systems (TBS), showed that for the specific Belgian situation (climate, installation costs, etc.) the potential TBS size reduction due to improved insulation was largely insufficient to compensate for the increased cost of the thermal insulation. See reference in footnote number 14.