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Influence of Thermal Insulation and Phase-Change Material on Energy Demand and CO_2-Emissions in Different European Climates

on behalf of BASF AG

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Contents

1 Introduction

The study at hand is investigating the influence of thermal insulation and phase-change material on energy demand of heating and cooling, and respectively summertime indoor climate for 6 different European locations: Warsaw, Frankfurt(Main), London, Paris, Rome, and Seville.

Subject matter to the survey is the effect of the following products (manufacturer information):

- Styropor®: BASF's expandable EPS for the fabrication of EPS-insulation boards. Styropor® is characterised by good thermal insulation capability, high pressure resistance, good shock absorption, low weight, and resistance to humidity. Applications: exterior insulation and finish systems (EIFS), impact sound insulation, insulation of uppermost storey's ceiling, insulation of steep roofs, insulation of basement ceiling, insulation of flat roofs, stone boards and prefabricated components.
- Neopor®: BASF's expandable EPS for the fabrication of EPS-insulation boards. By employing infrared absorbers, Neopor® achieves the same insulation performance as standard EPS using less material. Applications: exterior insulation and finish systems (EIFS), impact sound insulation, insulation of uppermost storey's ceiling, insulation of steep roofs, insulation of basement ceiling, insulation of flat roofs, stone boards and prefabricated components.
- Styrodur® C: extruded polystyrene rigid-foam (XPS) produced by BASF. Styrodur® is characterised by good thermal insulation capability, low water take-up, and high pressure resistance. Applications: Perimeter insulation, inverted roof, thermal bridge insulation, floor insulation, core insulation, steep roof insulation, ceiling insulation, frost protection for road and rail construction.
- Elastopor® H: Elastopor® H is an approximately 95% closed-cell polyurethane rigid-foam for the fabrication of foam and rigid-foam panels. When sprayed in multiple layers, Elastopor® H can be used as thermal insulation and jointless sealant simultaneously.
- Micronal® PCM: latent heat storage produced by BASF. Construction materials including Micronal® PCM stabilise indoor temperatures in the range of the phase transition. Micronal® is available from BASF in pulverised and liquid form, e.g. for the fabrication of plaster or gypsum plasterboards with latent heat storage capacity.

The survey on the insulation materials was carried out by means of an end-of-terrace house in residential use. For the investigation of Micronal® PCM phase-change material two rooms in an office building were considered.

2 Method of Calculation

2.1 The Building Simulation Programme DYNBIL

The space heat demand of all variants, investigated in this survey, was determined by means of dynamic thermal building simulation. This method allows detailed prediction of a building's thermal behaviour based on physical coherences. In contrast to the stationary method, also heat storage processes explicitly enter the calculation. The building is split into multiple zones so that rooms with different boundary conditions (utilisation, window areas, shading, orientation, designated temperature, geometry) can be investigated separately from one another. Factors that are included are, amongst others, thermal characteristics of components, effect of solar radiation, internal gains, heating, and cooling respectively, as well as interactions in between the zones. The simulation processes hourly values of the boundary conditions. Thus, it provides results for the temperature development for every zone of the model and its required heating and cooling power respectively.

The calculation was carried out using the dynamic building simulation program DYNBIL, developed by the PHI. Detailed comparison of results produced by DYNBIL with measurements in constructed projects yielded very good accordance. The program proved itself during several years of planning and thermal investigation of buildings. It is characterised by the following features [Feist 1999]:

- Thermal conduction and heat storage
  - Unstationary heat fluxes (multi-capacity network model) including one dimensional substitutes for thermal bridges
- Convective heat transfer
  - Temperature dependence of convective heat transfer for room surfaces
  - Temperature dependence of convective heat transfer for spaces between glazings
- Long-wave radiation exchange
  - Approximation of indoor radiation heat exchange by means of a two-node model while clearly separating radiation and convection
- Short-wave radiation
  - Influence of angle of incidence for radiation transmittance through the window
  - Shading of short-wave radiation
- Heat transfer on exterior surfaces
  - Convective heat transfer, depending on wind
  - Long-wave radiation exchange between exterior surfaces, ambiance, and radiation into the sky; atmospheric albedo
- Internal heat sources
  - Consideration of different thermal transport mechanisms

- Influence of heat output
  - Assessment of indoor climate by means of operative temperatures

3 Variations in Thermal Insulation Standard

3.1 The Calculation Process

The positive influences of thermal insulation on heat demand and energy consumption in cold climates are out of questions from a scientific point of view, yet still insufficiently recognized in broad public. Commonly the extent of achievable energy savings due to thermal insulation measures and the benefit when employed in warmer climates, especially in regard to summertime periods, is unclear.

This section identifies the consequences of different thermal insulation levels for the following factors:

- Space heat demand, i.e. the amount of energy which needs to be supplied to a room during one year in order to ensure an operative indoor temperature of 20 °C.
- Heating energy demand, i.e. the amount of energy in the form of e.g. heating oil or natural gas which needs to be supplied to the heating system during one year in order to ensure an operative indoor temperature of 20 °C.
- Useful cold demand, i.e. the amount of energy which needs to be removed from the building by means of an active cooling system in order to confine indoor air temperature to a maximum of 25 °C.
- Electricity demand for space cooling, i.e. annual electricity consumption for space cooling resulting for typical annual performance factors of common split devices.
- Peak temperature, i.e. the highest hourly mean temperature which appeared in any of the rooms (zones 1 to 6) during one year. In general, the highest temperatures occur in zone 4 which is south-oriented and located under the roof (cf. Figure 1).
- Frequency of overheating, i.e. the number of hours in which the operative indoor temperature exceeds 25 °C, *in case no active cooling is installed*. The mean value, weighted according to living area, of this frequency is displayed.
- Primary energy demand for space heating and cooling. Here it is assumed that active cooling is employed. The auxiliary electricity demand of the heating system was considered. In the case of the cooling system the auxiliary electricity demand is already incorporated in the annual performance factor of the cooling device.
- CO_2 emissions for space heating and cooling.

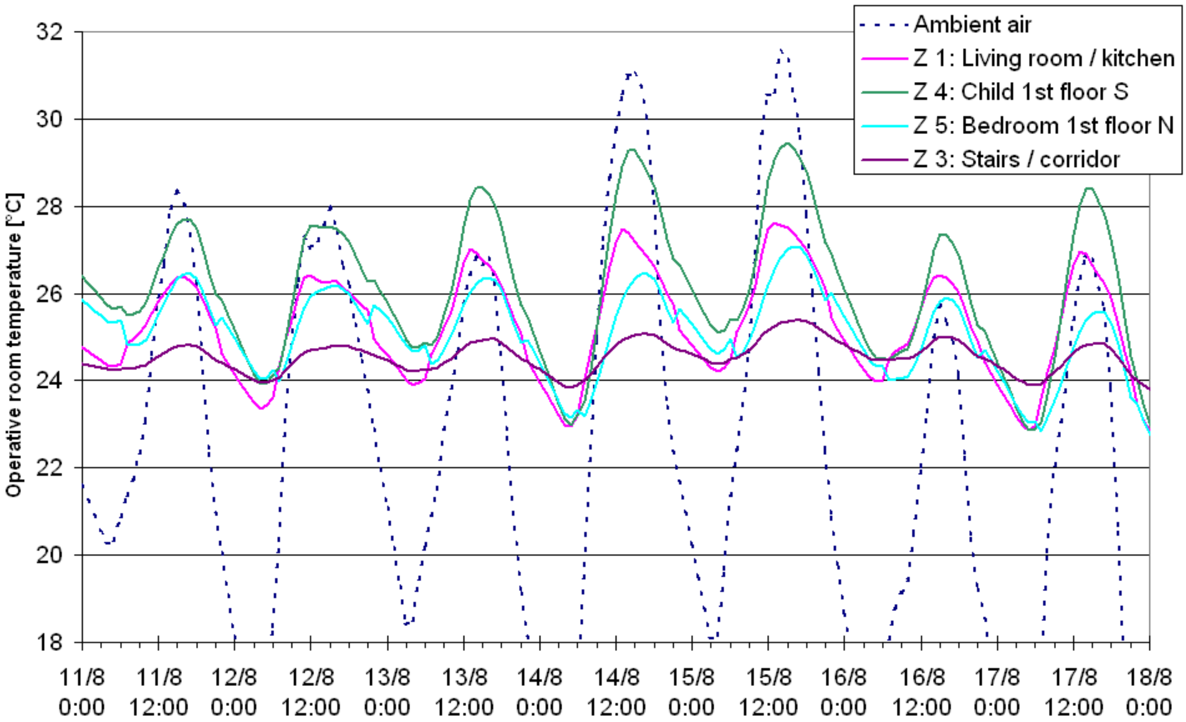


Figure 1: Example for the temperature sequence in summertime (Frankfurt, Germany, thermal insulation standard 'minimal', no active cooling)

3.2 Example Building

The end-of-terrace house, shown in Figure 2, served as a basis for the simulation calculations. The building has two storeys and a basement which is contained inside the building's thermal shell. Nevertheless, the basement is not heated. The building was constructed as a solid structure, the living area amounts to 120 m².

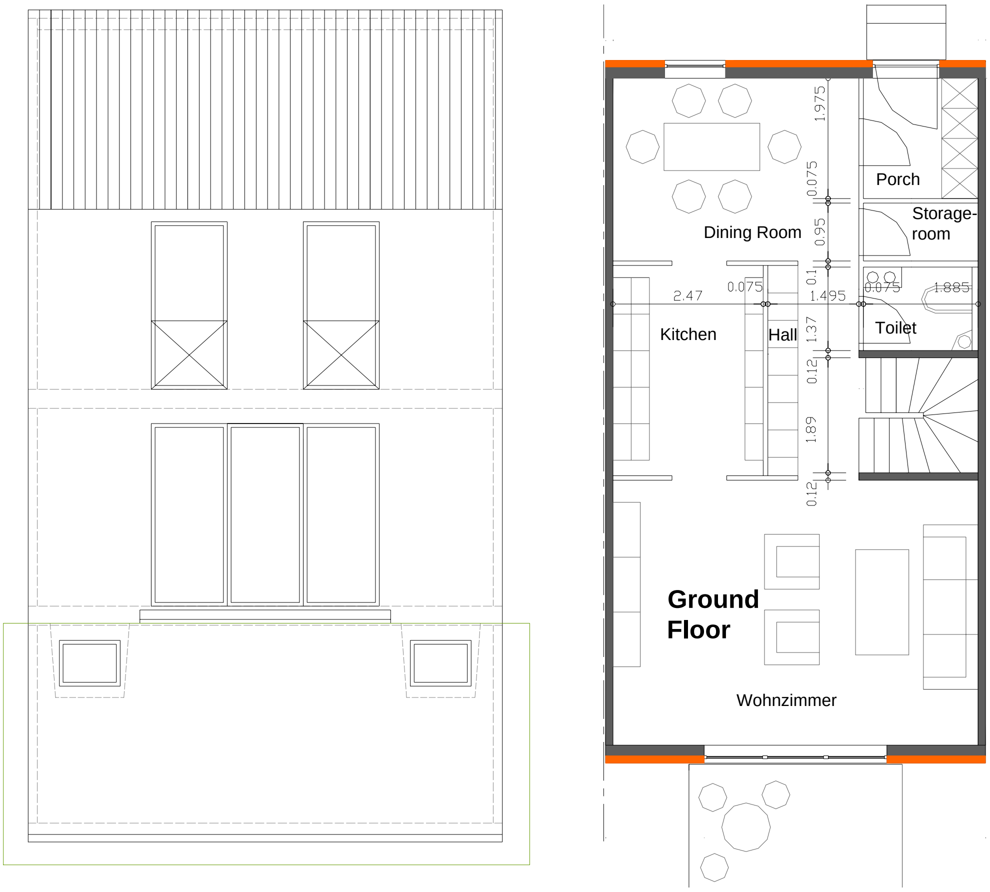


Figure 2: South view and ground floor plan of the end-of-terrace house which was used for the study on thermal insulation influence (cf. Appendix)

A detailed description of the applied simulation model can be found in the appendix.

Different thermal protection involves not only the heat insulation applied on walls, roof, and basement. Good thermal protection of opaque elements, good thermal quality of the windows, and reduction of ventilation heat losses call for one another. That is why four different example buildings, in which the components have been reasonably harmonised with each other, were investigated

Since the climate in the Mediterranean differs considerably form the northern areas of Europe, certain details for the example buildings in Seville and Rome were chosen deviating from the ones in other locations. South of the Alps, the thermal protection standard was generally chosen to be lower. The roof is realised as a solid construction instead of a lightweight construction. The windows are equipped with shutters shielding solar radiation in summertime. Furthermore, in the variants without air-conditioning the windows are not only tilted but widely opened in order to cool down the building.

3.3 Characteristics of the examined BASF-Products

For the heat conductivity the nominal values λ_D are continually used instead of the rated values that are usually used for design purposes (as required by many national laws). Nominal values are directly deduced from measurements, taking a statistical spread and an ageing allowance into account. Hence, they correspond to the average heat conductivity which can be expected during lifetime.

The following data on the material was utilised:

Application	Material	BASF-Product	Density [kg/m³]	Heat capacity [J/(kgK)]	Heat conductivity [W/(mK)]
Wall	IR-EPS	Neopor® (Raw material)	15	1210	0.032
Wall[1]	EPS	Styropor® (Raw material)	15	1210	0.038
Roof	PUR	Elastopor® H[2] (Raw material)	30	1500	0.023
Basement	XPS	Styrodur® 3035 CS (Finished product)	33	1500	0.032 – 0.04[3]

[1] The simulation calculations were carried out using Neopor®. Styropor® can be used alternatively. However, in this case the insulating material's thickness must be chosen 19 % higher.

[2] Elastopor® H is a product of the BASF group affiliate Elastogran. The calculation is carried out assuming a pentane-driven foam with a vapour-impermeable top coat.

[3] Depending on thickness: 0.032 below 30 mm, 0.034 up to 60 mm, 0.036 up to 80 mm, 0.038 up to 160 mm, 0.04 above 160 mm.

3.4 Results

As mentioned before, at first the simulation calculations were carried out for four different thermal insulation standards in comparison to each other:

- 'minimal': The building is equipped with a certain minimum thermal protection which is sufficient to prevent condensation on surfaces. The U-values for the roof are 1.0 W/(m²K) (massive roof south of the Alps) and 0.84 W/(m²K) respectively (rafter roof north of the Alps) and 1.16 W/(m²K) inside the walls. The basement's roof and walls as well as the floor slab are not insulated. Many existing old buildings feature thermal protection standards which in any case are no better than the 'minimal' thermal insulation standard utilised here.
- 'moderate': The old building's components are equipped with additional thermal insulation. The thermal insulation standard matches roughly the one employed for a building constructed in recent years.
- 'good': For this case the thermal protection was improved once more. In different studies ([Kah 2005], [Rabenstein 2006]), the optimal cost effectiveness of insulation material thicknesses was determined, providing that no interdependencies with other costs exist (e.g. subsidies or savings in building services due to improved thermal insulation). Here the findings of such optimisation calculations served as a guideline when obtaining the thicknesses of insulation material. The building approximately represents a low-energy building.

- 'very good': Thermal protection compares with the (German) Passive House standard. South of the Alps, the level of thermal protection was assumed to be close to German legal requirements on newly constructed buildings.

For reasons of clarity, the building characteristics were no further differentiated for the climatic zone north of the Alps. The same holds for the two climatic zones south of the Alps. The following table summarises the thicknesses of insulation material and U-values of the exterior structural components for the studied cases.

North of the Alps

Case	Insulation roof [cm]	Insulation wall [cm]	Insulation floor slab [cm]	Insulation basement wall [cm]
minimal	0	0	0	0
moderate	10	8	4	4
good	15	15	8	8
very good	30	30	20	20

Case	U-value roof [W/(m²K)]	U-value wall [W/(m²K)]	U-value floor slab [W/(m²K)]	U-value basement wall [W/(m²K)]
minimal	0.839	1.158	4	4
moderate	0.181	0.297	0.694	0.699
good	0.13	0.18	0.4	0.4
very good	0.07	0.098	0.19	0.19

South of the Alps

Case	Insulation roof [cm]	Insulation wall [cm]	Insulation floor slab [cm]	Insulation basement wall [cm]
minimal	0	0	0	0
moderate	4	4	0	2
good	8	10	0	4
very good	15	15	0	6

Case	U-value roof [W/(m²K)]	U-value wall [W/(m²K)]	U-value floor slab [W/(m²K)]	U-value basement wall [W/(m²K)]
minimal	1.019	1.158	4	4
moderate	0.368	0.473	4	1.139
good	0.224	0.251	4	0.699
very good	0.133	0.18	4	0.496

The example building's thermal characteristics and the results illustrated in section 3.1 are summarised in the graphs on the following pages.

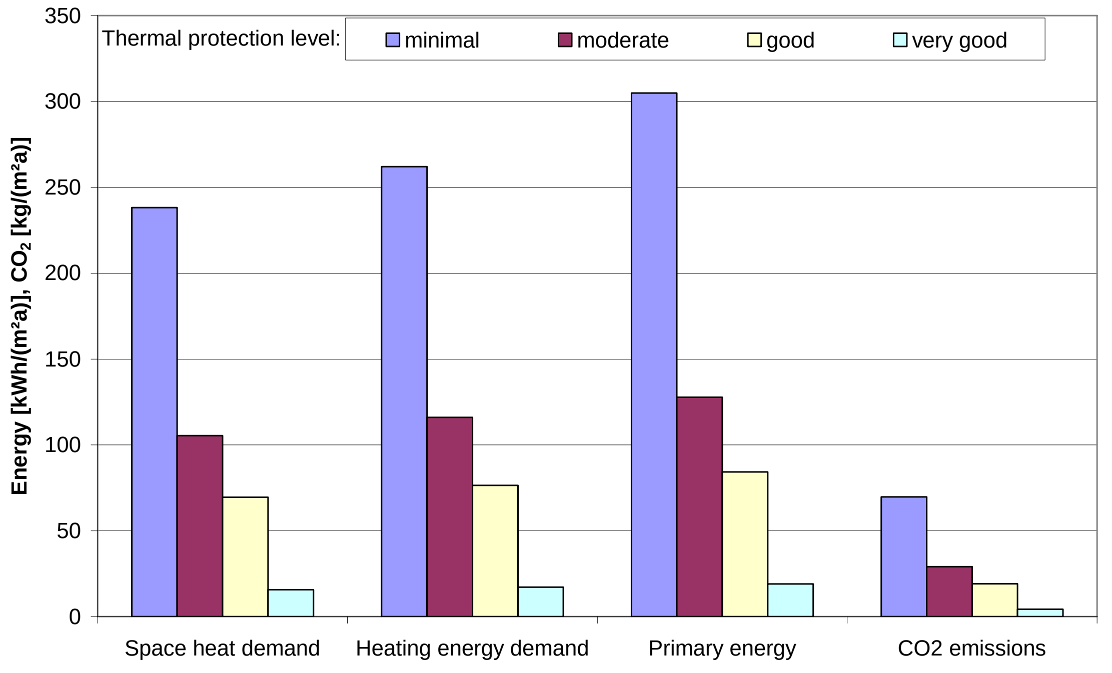
The simulation showed that north of the Alps indoor cooling and overheating are insignificant for the example building: The computed cooling energy demand was below 2 kWh/(m²a) for all cases; without a cooling system indoor temperatures exceed 25 °C for less than one week a year. Hence, these data are not shown in the diagrams.

In any case, it is found that energy demand and environmental load can be reduced considerably by means of improved thermal protection. In the same manner, buildings with improved insulation decrease cooling energy demand and summer comfort increases for southern climates.

In most cases, useful cooling energy demand is much lower than heating energy demand under the assumed preconditions (i.e. support of active cooling by moderate ventilation through windows when reasonable; cooling of air temperature to 25 °C, cf. attachment). Only in Seville, this relation inverts for the well-insulated examples: In these cases hardly any thermal heat is required, whilst a useful cooling demand of approx. 10 kWh/(m²a) remains.

Warsaw

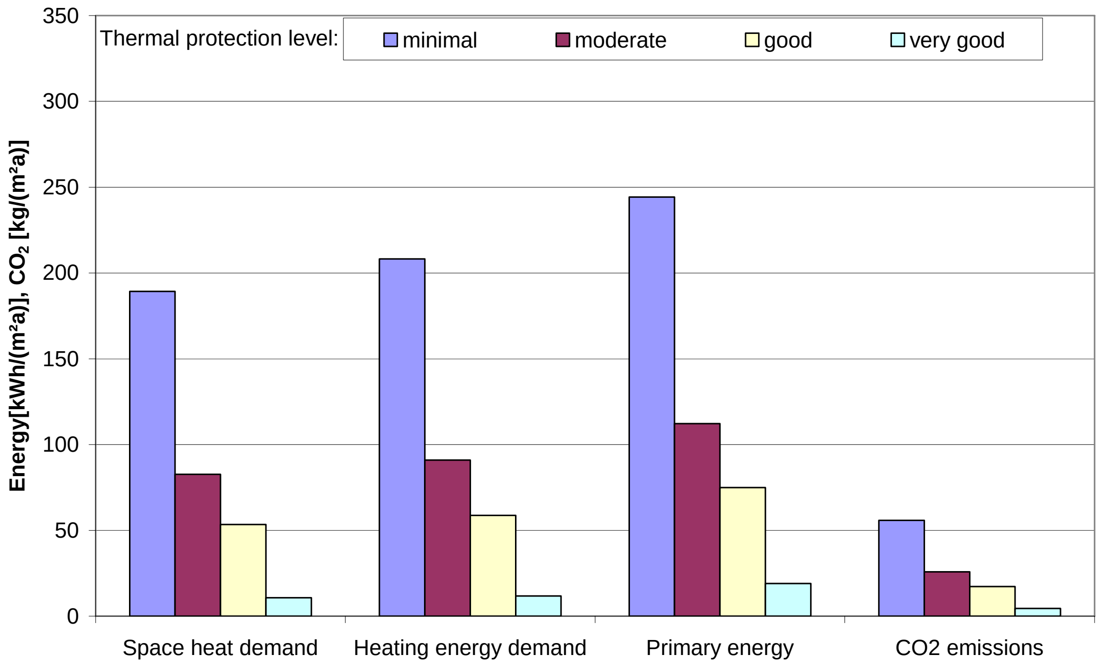
Thermal insulation standard



minimal	Insulation thickness: no insulation Standard double glazing, U ≈ 2.8 W/(m²K), g ≈ 0.76* 68 mm wooden window frame Air tightness: n_{50} = 6 h^{-1} Window ventilation
moderate	Insulation thickness: roof 10 cm, wall 8 cm, basement wall and floor slab 4 cm Double low-e glazing, U ≈ 1.2 W/(m²K), g ≈ 0,53* 68 mm wooden window frame Air tightness: n_{50} = 4 h^{-1} Exhaust air system
good	Insulation thickness: roof 15 cm, wall 15 cm, basement wall and floor slab 8 cm Double low-e glazing, U ≈ 1.2 W/(m²K), g ≈ 0.53* 68 mm wooden window frame Air tightness: n_{50} = 1.5 h^{-1} Exhaust air system
very good	Insulation thickness: roof 30 cm, wall 30 cm, basement wall and floor slab 20 cm Triple low-e glazing, U ≈ 0.51 W/(m²K), g ≈ 0.52* Passive house window frame Air tightness: n_{50} = 0.5 h^{-1} Balanced ventilation system with 85% heat recovery

* Nominal values of used glazing. The simulation program takes the interdependency of glazing attributes and the respective boundary conditions into account.

Frankfurt



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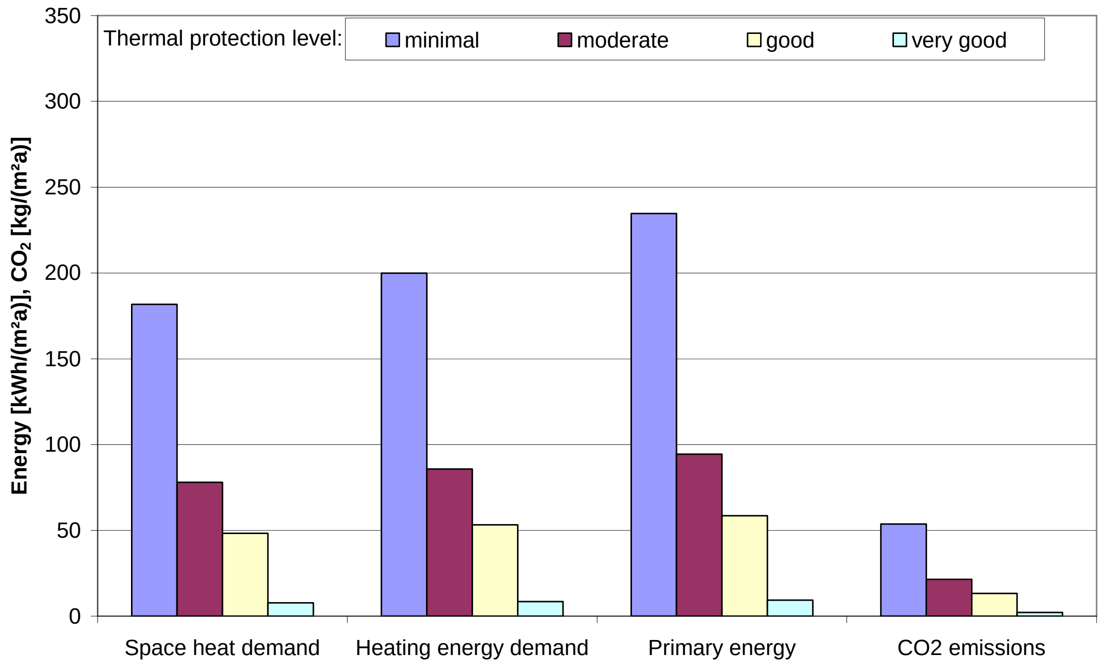
London

Thermal insulation standard



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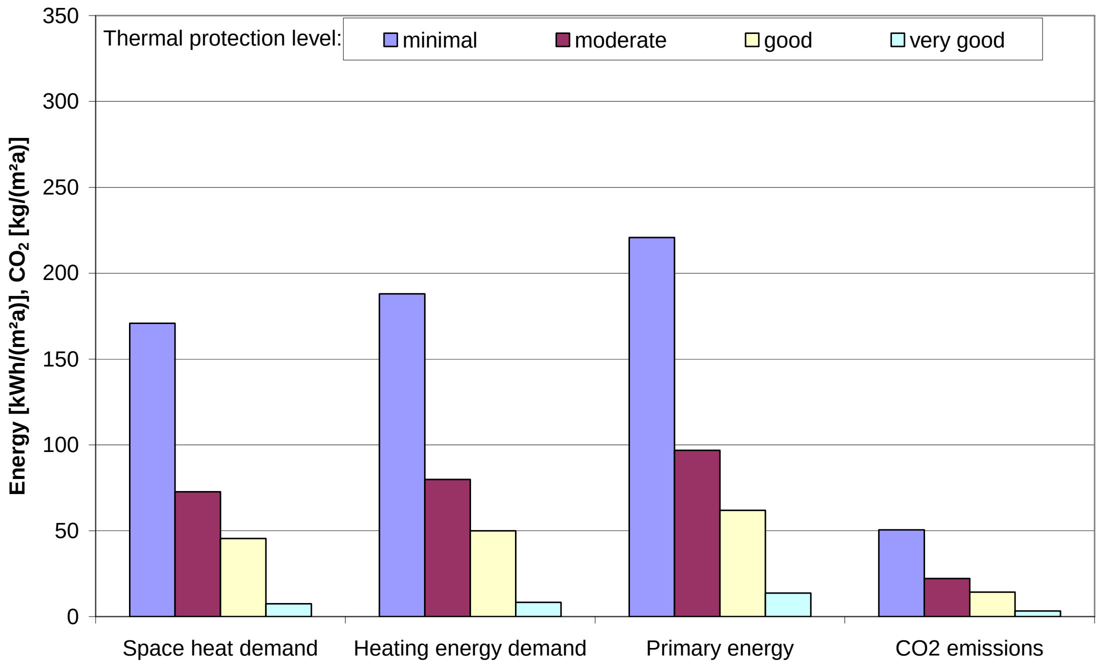
Paris

Thermal insulation standard



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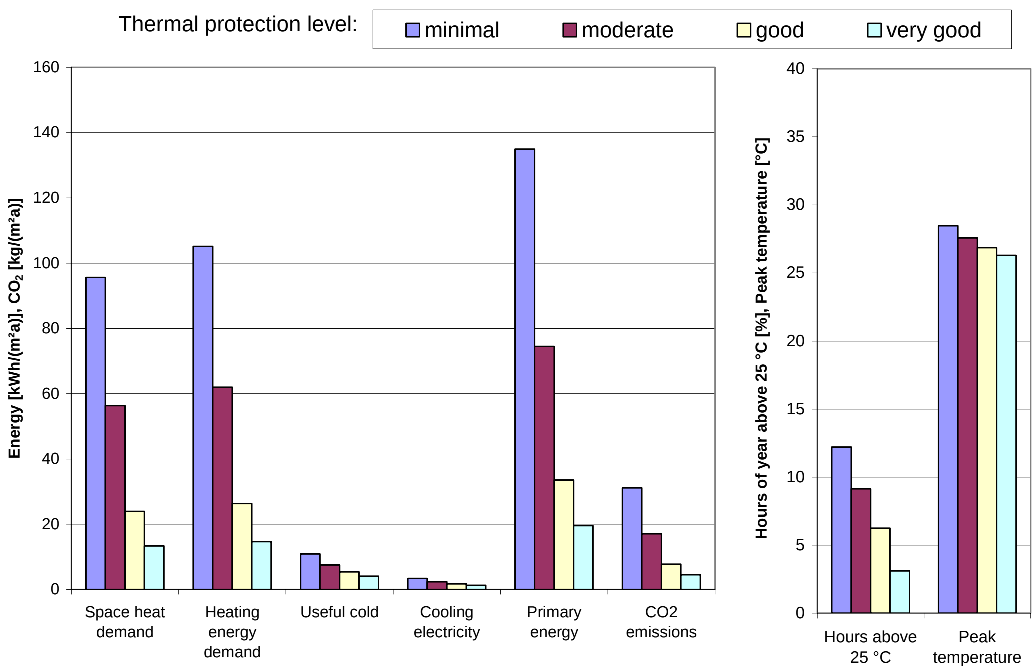
Rome

Thermal insulation standard	
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moderate	Insulation thickness: roof 4 cm, wall 4 cm, basement wall 2 cm, floor slab 0 cm Single-glazing, U ≈ 5.7 W/(m²K), g ≈ 0.85* 45 mm wooden window frame Air tightness: n_{50} = 4 h^{-1} Exhaust air system
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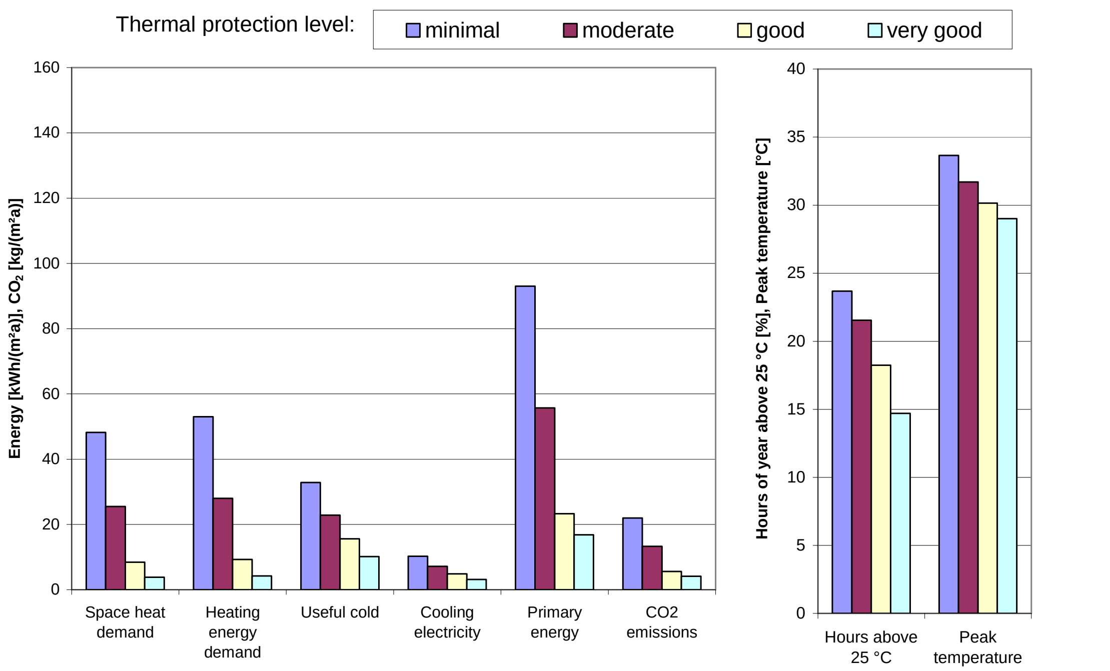
* Nominal values of used glazing. The simulation program takes the interdependency of glazing attributes and the respective boundary conditions into account.

Seville

Thermal insulation standard	
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* Nominal values of used glazing. The simulation program takes the interdependency of glazing attributes and the respective boundary conditions into account.

4 Profitability of Thermal Insulation

4.1 Boundary Conditions and Method of Calculation

In section 3.4 it was shown that, by improvement of thermal protection, vast environmental load reduction and energy savings can be achieved for all investigated climates. In this section, the question of profitability of thermal insulation measures is illuminated.

The calculation of profitability is carried out by means of the present value method. Here it is already considered that sums which will flow in the future have to be accounted for with an accordingly lower value. That is due the interest calculation of the assets raised for additional expenses of construction. For the case at hand, this discounting was carried out for the economised energy costs. The premised true interest rate is 3.5% (market interest rates of mortgages, nominal, no subsidies).

The insulation measures' lifetime is generally assumed to be 50 years. This is also the period used for the calculation of profitability.

Energy costs were investigated for two different variants. Variant 1 merely presumes a moderate real increase of prices over the studied period. The prices orient themselves on the energy purchasing costs in the year 2005 in Germany.

Variant 2 supposes an increase in energy costs in the order of magnitude of the presumed real interest rate of 3.5%. In this case, the present value method would correspond barely to a stationary cost-benefit analysis without consideration of interest effects. Nevertheless, it is taken into account here that energy costs currently determine electricity costs by only approximately one third. In this variant, the respective increase in prices affects only that one third.

The following table shows the resulting mean values of energy prices for the period of observation of 50 years.

	Variant 1: 0 % Energy price increase	Variant 2: 3,5 % Energy price increase
Thermal heat	0.061 €/kWh	0.167 €/kWh
Electricity	0.17 €/kWh	0.268 €/kWh

In order to be able to determine the required investments for thermal insulation, it is necessary to identify the costs for one *additional* centimetre of insulation. The prices for thermal insulation may vary with the respective building project, as construction prices do in general. Based on a study for the surveyed countries, values for the variable costs of thermal insulation material were developed i.e. including the additional centimetre insulation material and possible additional costs for longer fasteners, deeper windowsills, more costly scaffoldings, etc.. The estimate of costs may serve to assess the ecological effects of different thicknesses of insulation material for new buildings. Thus, it is assumed that insulation material is applied anyway; the costs for scaffolding, mount, plastering, etc. are then almost independent from insulation material thickness.

In case an application of thermal insulation is projected anyway, this estimate of costs can be used also for wall and roof refurbishment of old buildings. Here as well the better part of costs is independent from insulation material thickness. However, the cost differences for different insulation material thicknesses, calculated in the following, must not be misinterpreted as costs of an energetic refurbishment of old buildings.

4.2 Profitability of Thermal Insulation in Roof, Walls and Basement

The economic benefits become most apparent when considered at the example building itself and, in doing so, the effects of insulation on opaque components are analysed separately from other components. For a start the energy savings which result when roof, walls, and basement are accomplished using the insulation standard ‘good’ instead of the minimal thermal protection of old buildings were analysed by means of the simulation. Windows, ventilation system, etc. remain on the respective higher standard so that only the effect of thermal insulation is considered; indoor temperature in wintertime is 21 °C.

In the second step, the additional costs which result form better thermal insulation were determined. Here it is assumed that the building with minimal thermal protection has a thermal insulation of the same system as it is used in the example, yet with considerably lower thickness. In this case, the additional costs of better thermal insulation are determined only by the variable thermal insulation costs mentioned above.

The following table shows for the 6 different climates:

- investment costs for better thermal insulation
- energy cost savings per annum for unchanged energy costs
- static payback period, i.e. the time after which the investment would have paid off for a stationary consideration
- present value of net profit due to improved thermal insulation for both variants of energy price development

	Warsaw	Frankfurt	London	Paris	Rome	Seville
Investment [€]	5500	5500	5500	5500	2800	2800
Savings [€/a]	1160	940	930	870	470	360
Static payback period [a]	4.7	5.8	5.9	6.3	5.9	7.8
Present value gain, variant 1 [€]	21700	16600	16400	15000	8300	5600
Present value gain, variant 2 [€]	51600	40900	40500	37600	20000	13200

In all climates, the improved thermal insulation yields net profits during its lifetime. As anticipated, savings are maximal for the coldest climates. Nonetheless, improved thermal insulation can achieve economic profit even in the warm climate of Seville. In all cases, the static payback period is notably less than 10 years.

5 Phase-Change Materials

5.1 Phase-Change Material: Micronal® PCM

A material's transition from solid to liquid phase often allows it to absorb large quantities of heat without significantly changing its temperature. This effect can be exploited to stabilise ambient temperatures inside buildings. In order to do so, melting temperatures must be in a range that is relevant to housing requirements. Phase Change Materials (PCM) have to be thermally accessible from the rooms and the molten PCM must not soak construction materials. This requirement can be met by microencapsulated paraffines as part of gypsum plaster or gypsum wallboards. The finished product can be processed like conventional plasters and building boards respectively.

In the following, the product 'Micronal® PCM SmartBoard™' will be analysed in the application as a support for air-conditioning in an office building. Micronal® PCM SmartBoard™ is a plaster wallboard of 15 mm thickness containing a 26 % mass fraction of microencapsulated paraffines.

5.2 Simulation Model

Phase-change materials are especially efficient when indoor temperatures regularly rise strongly and fall again during one day, e.g. due to large solar or internal gains. Typical examples are offices, but also in kindergartens, schools, lecture halls, gastronomy, or canteen kitchens there exist certain periods having a distinct daily trend which may result in a charge and discharge of the accumulator during one day.

In the simulation calculations a single office was examined as a representative of a bigger building (Figure 3). The building was realised completely in lightweight construction. The offices on the north and south side were assumed to be small single offices. The inside dimensions hold 1.80 m width, 4 m length, and 2.80 m height. The windows are realised with 1.80 m height and 1.60 m width. The corridor has a width of 1.20 m.

The exterior wall is insulated by 8 cm of Neopor® in Spain and Italy and 15 cm north of the Alps, respectively. The windows are equipped with double low-e glazing north of the Alps; south of the Alps standard double glazing is employed. The office is oriented to north / south, there is no exterior temporary shading installed.

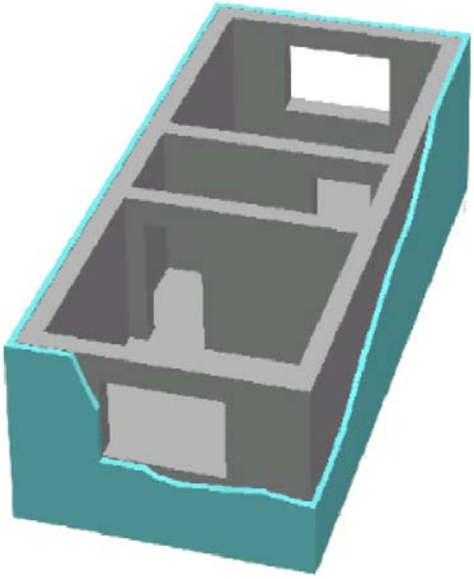


Figure 3: Example object structure used for simulation calculations with Micronal® PCM (not according to scale, picture: BASF)

The office has high internal loads: It is occupied by one person, being present from Monday to Friday 8 to 18 o'clock with one hour lunch break. During that time, office machines (PC, monitor, fax, etc.) require a power input of 220 W. Additionally there is a constant base load of 15 W. The internal loads for a workday sum up to 400 Wh/(m²d).

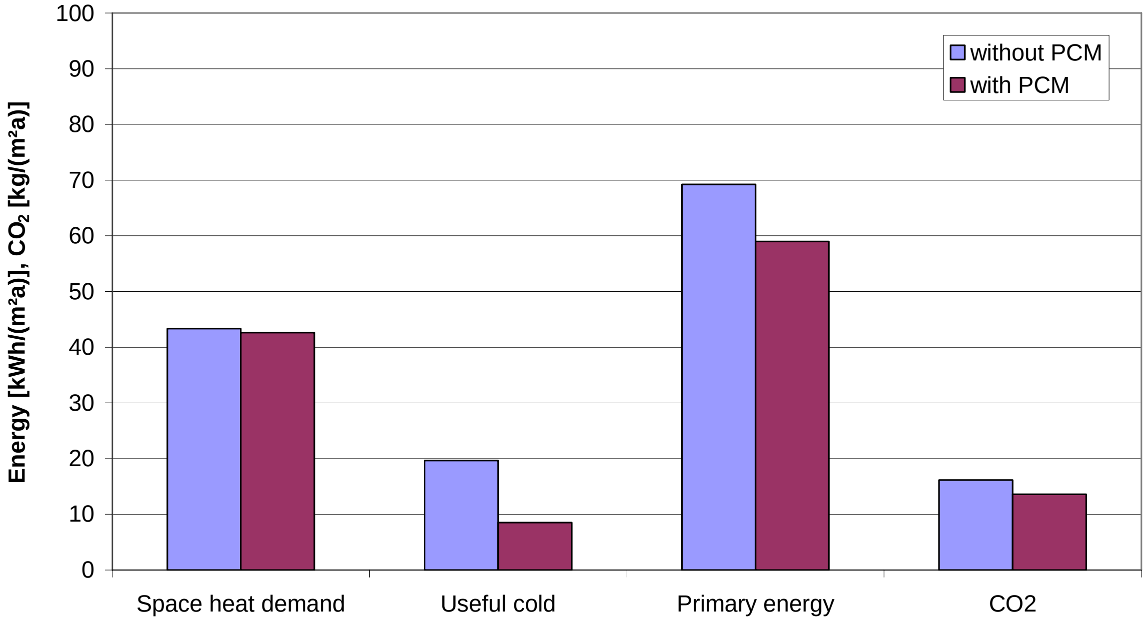
Due to the high internal loads, active cooling of the offices is necessary for all examined climates. It limits indoor air temperature to 25 °C. In order to save energy the air-conditioning system is supported by nightly tilted windows. Hence surface temperatures fall below the melting point of the Micronal® PCM SmartBoard™ at night on several days of the year. Already a temperature difference of 1 K causes a flow rate of 40 m³/h through the two tilted windows. They have a height of 1.80 m and are located in every office. By means of an appropriate control, windows will be closed when indoor temperature falls too low at night or air change rates become too high (above 200 m³/h per office).

The simulation calculations presume that surfaces of structural elements which are thermally active are primarily accessible from the room. Grave detachments of Micronal®-containing layers, for instance by large wall units, are not considered.

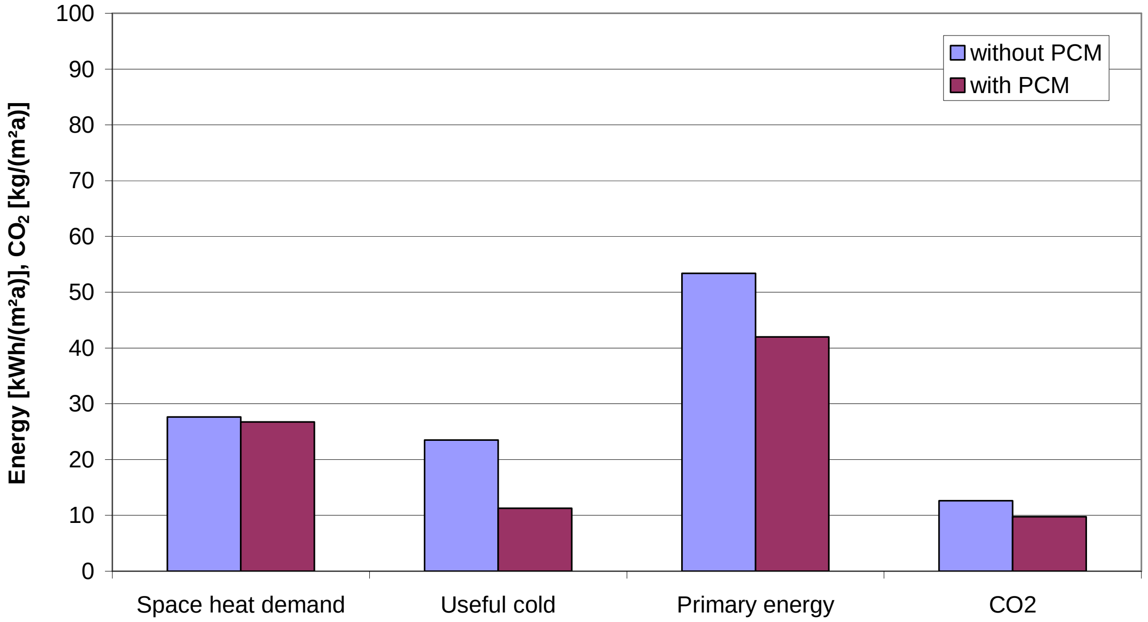
5.3 Simulation Results

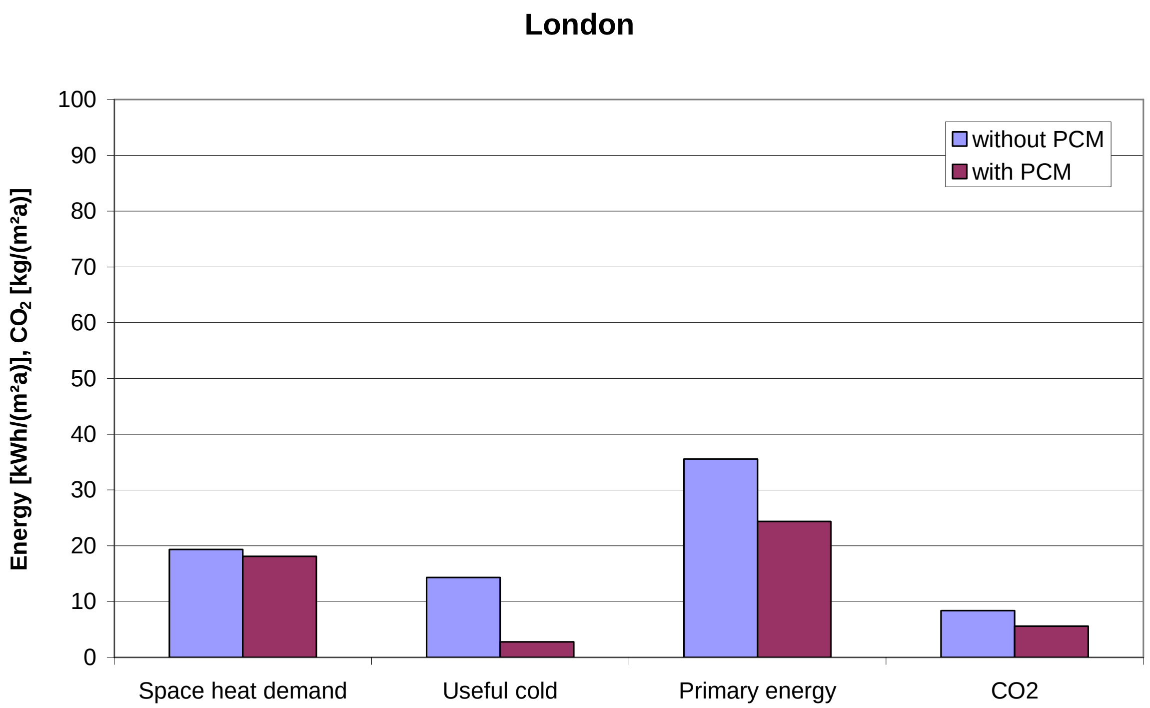
In the following, the most important characteristic values resulting from the simulations are shown.

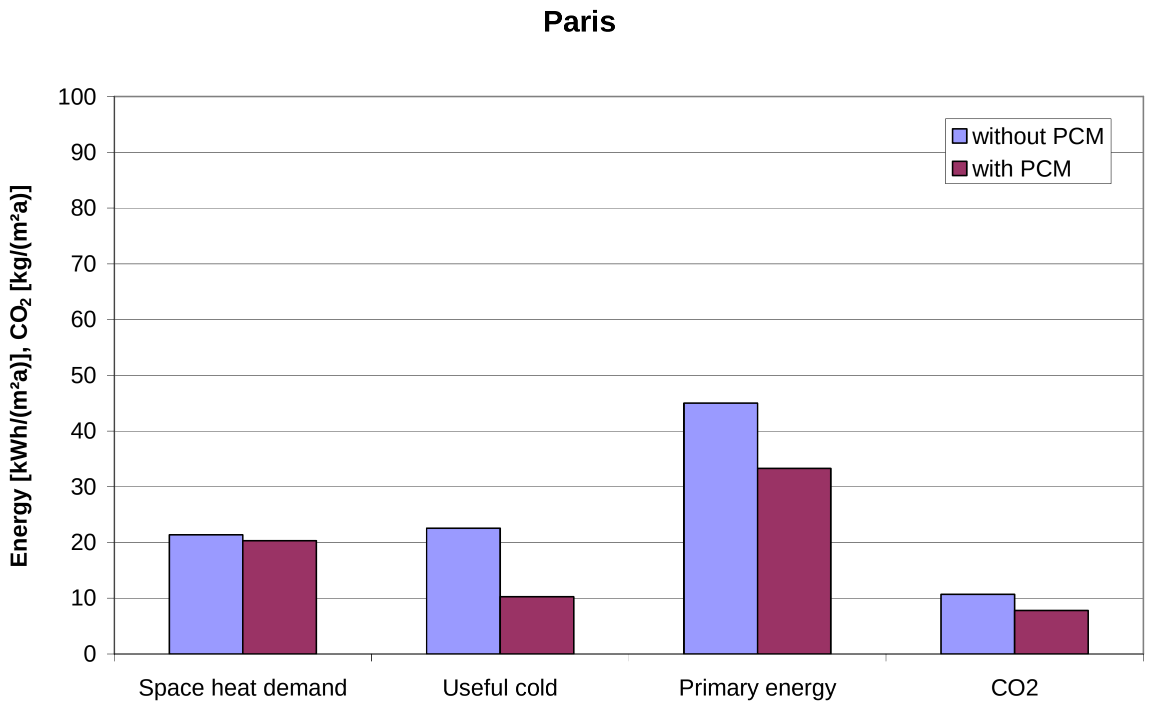
Warsaw

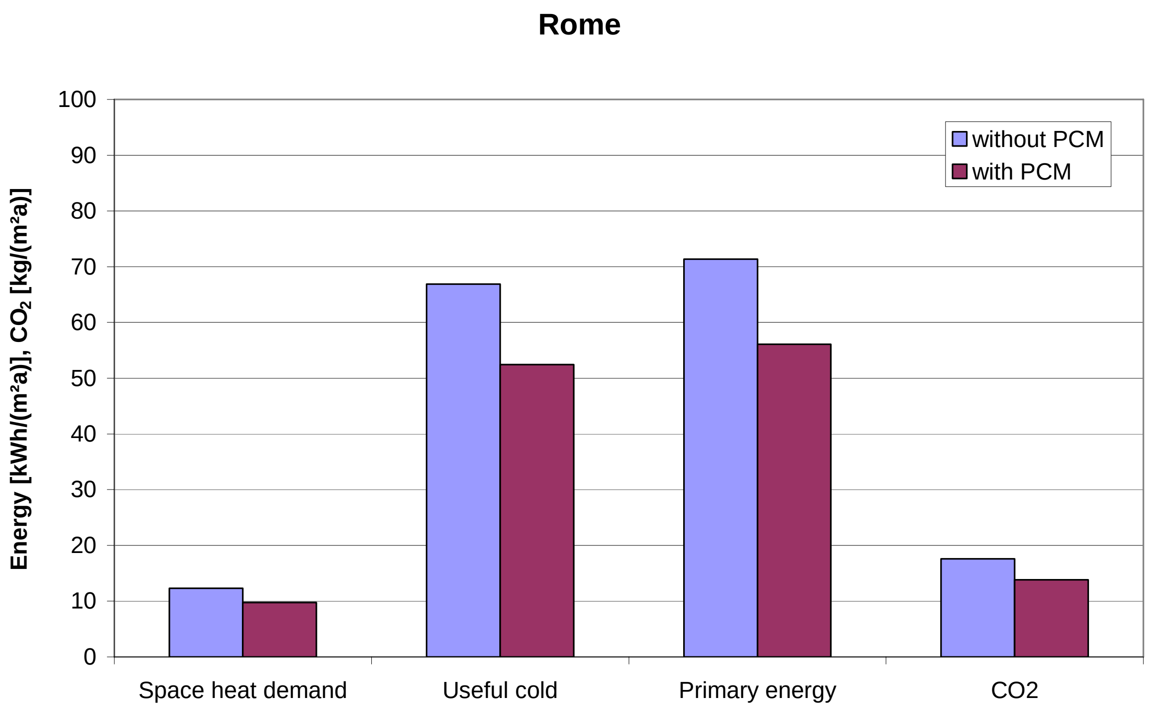


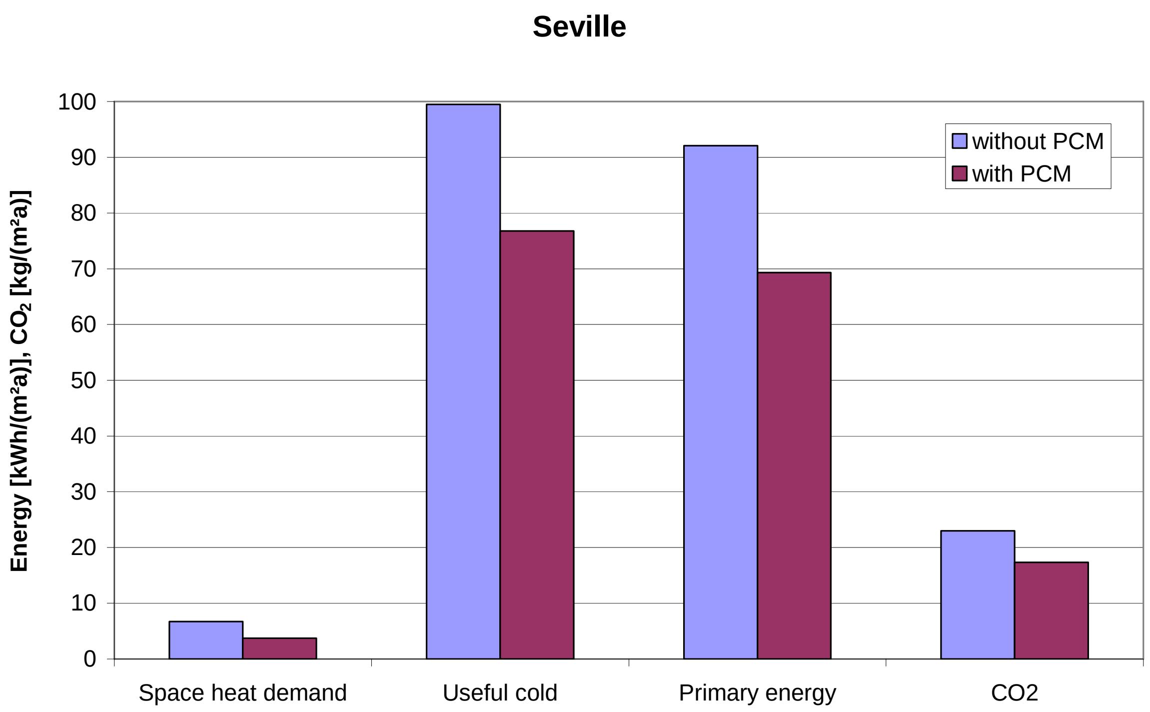
Frankfurt




London
100
90
80
70
60
50
40
30
20
10
0
Energy [kWh/(m²a)], CO2 [kg/(m²a)]
without PCM
with PCM
Space heat demand
Useful cold
Primary energy
CO2


Paris
100
90
80
70
60
50
40
30
20
10
0
Energy [kWh/(m²a)], CO2 [kg/(m²a)]
without PCM
with PCM
Space heat demand
Useful cold
Primary energy
CO2


Rome
100
90
80
70
60
50
40
30
20
10
0
Energy [kWh/(m²a)], CO_2 [kg/(m²a)]
without PCM
with PCM
Space heat demand
Useful cold
Primary energy
CO2


Seville
100
90
80
70
60
50
40
30
20
10
0
Energy [kWh/(m²a)], CO_2 [kg/(m²a)]
without PCM
with PCM
Space heat demand
Useful cold
Primary energy
CO2

Employment of Micronal® PCM SmartBoard™ has in all cases positive effect on both the rooms' heat and cold demand. When it comes to cooling the effect is more relevant than for heating since the supportive night-ventilation yields higher temperature differences. Thus, the melting temperature range of Micronal® PCM SmartBoard™ is crossed more often.

5.4 Profitability

5.4.1 Theoretical Boundaries

The maximum effect of the melting enthalpy of Micronal® PCM SmartBoard™ on a building's energy balance can easily be assessed. This evaluation is carried out in the following.

In the temperature range of 21 to 25 °C, 1 m² Micronal® PCM SmartBoard™ absorbs 357 kJ of heat. That is 313 kJ more than for a regular gypsum wallboard. The, by far, predominant part of this difference is due to the paraffin's heat of fusion. Around 3% of that is accountable to the already higher heat capacity of Micronal® PCM SmartBoard™ compared to regular gypsum wallboards.

In case a building requires cooling at daytime and heating at night every day and further the temperature range of 21 to 25 °C is crossed from both sides once a day, the 313 kJ, computed above, can be saved as both heating and cooling energy. For one year 130 MJ or 31.7 kWh of useful heat and respectively cold energy are saved per square meter of Micronal® PCM SmartBoard™ under optimal exploitation conditions (365 days a year). Assuming the energy prices and the system's rate of utilisation used for this study, and costs for Micronal® PCM SmartBoard™ being 40 €/m², a payback period of 11 years results.

It must be kept in mind that the actual saving is usually by far lower: In most of the buildings, both heating and cooling is not necessary every day and therefore the *PCM's* temperature does not vary completely through the above-named range. Furthermore, dynamic effects reduce the material's effectiveness. The actual saving, achievable with Micronal® PCM SmartBoard™, can only be assessed by means of a dynamic thermal building simulation under the boundary conditions of the particular case.

5.4.2 Simulation Results

The savings in operating costs, achievable under the assumed boundary conditions, can be calculated from the simulation calculations as documented in section 5.3. Based on the square meter Micronal® PCM SmartBoard™ deployed, these are summarised in the following table:

Saving [€/(m² PCM a)]						
Warsaw	Frankfurt	London	Paris	Rome	Seville	theoretic boundary
0.38	0.42	0.40	0.42	0.51	0.80	3.62

5.4.3 Further Aspects of the Economy of Micronal® PCM SmartBoard™

The basic principle of passive cooling is to harmonise different components with each other in a way that a working building results. That is, passive cooling can usually not be achieved by one measure alone. There is always a set of measures necessary. Besides Micronal® PCM SmartBoard™, these may be of the following example:

- energy efficient implements
- energy efficient lighting
- free aeration by means of windows or ventilation flaps at night
- mechanical ventilation at night
- effective, i.e. exterior and temporary, shading
- fixed shading devices
- thermal insulation of exterior building components
- colouring of exterior building components
- large thermal mass
- cold recovery by means of the ventilation system
- evaporative cooling
- earth-to-air or brine-to-air heat exchanger
- geothermal probes

A conclusive passive cooling concept may make active cooling redundant. The investment costs of a complete climate control unit (heating, cooling, humidification, dehumidification) can be estimated with 2000 to 2600 € per workstation. It has a lifetime of only 15 years [Recknagel 2003]. Moreover, considerable costs of 3.5% of total investment costs have to be added for maintenance and repair every year. These are much lower for many passive components; e.g. for Micronal® PCM SmartBoard™ there are none. If such a complete climate control unit can be made redundant by means of a passive cooling concept which may also include Micronal® PCM SmartBoard™, the profitability of the concept is often ensured alongside.

6 Summary

This study investigated the influence of different BASF-products on the energy budget of buildings by means of dynamic thermal building simulation. It falls into two parts: The first part deals with the consequences of thermal insulation containing the materials Neopor®, Styrodur® C, and Elastopor® H on a residential end-of-terrace house. The second part monitors the effect of Micronal® in an office building with high occupation density. The calculations were carried out for each of the six different climates of Warsaw, Frankfurt, Paris, London, Rome and Seville.

In the investigation of thermal insulation, 4 different insulation standards (this refers not only to thermal insulation of the roof, walls and floor slab, but also to window quality and ventilation) were compared. It turned out that improved insulation has several advantages in all the climates investigated.

- Space heat demand is reduced.
- Thus also the building's energy demand for space heating decreases.
- The heat quantity that needs to be disposed of in the warmer climates by air-condition is decreased. Electricity demand for space cooling is reduced accordingly.
- Consequently primary energy demand and CO_2 emissions decrease.
- Effectiveness of increased night ventilation for the purpose of space cooling without air-conditioning is improved: The number of hours above 25 °C and the peak temperatures decrease.

The cost-benefit analysis concluded that also economic benefits can be achieved by means of improved thermal protection. In case roof, walls, and floor are insulated to the standard 'good' (i.e. depending on the structural element 8 to 15 cm of thermal insulation north of the Alps and 4 to 10 cm south of the Alps) instead of 'minimal' (minimal thermal protection to avoid condensation on surfaces), the payback period for the additional investment costs is 4 to 8 years depending on the respective climate. Already with today's energy prices, considerable economic advantages result due to the high lifetime of thermal insulation.

The advantages of the phase-change material (PCM) Micronal® become especially apparent when considering lightweight buildings under intensive utilisation and the respective fluctuation in temperature. Indoor climate is stabilised in case Micronal® PCM SmartBoard™ is equipped instead of conventional gypsum plasterboard. For the investigated office building, equipped with cooling supported by night ventilation, heat and cold demand were reduced for all climates; primary energy demand decreases, depending on climate, by 15 to 32 percent. The effects on cold demand are substantially more distinct than on space heat demand.

As part of a passive cooling concept which makes a conventional air-conditioning unit redundant the application of Micronal® may become also financially rewarding. In particular, the high lifetime and the absence of maintenance costs have a positive effect.

7 References

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[Schossig 2005] Schossig, Peter: Personal memorandum of Dec 2nd, 2005 and Jan 3rd, 2006

Appendix

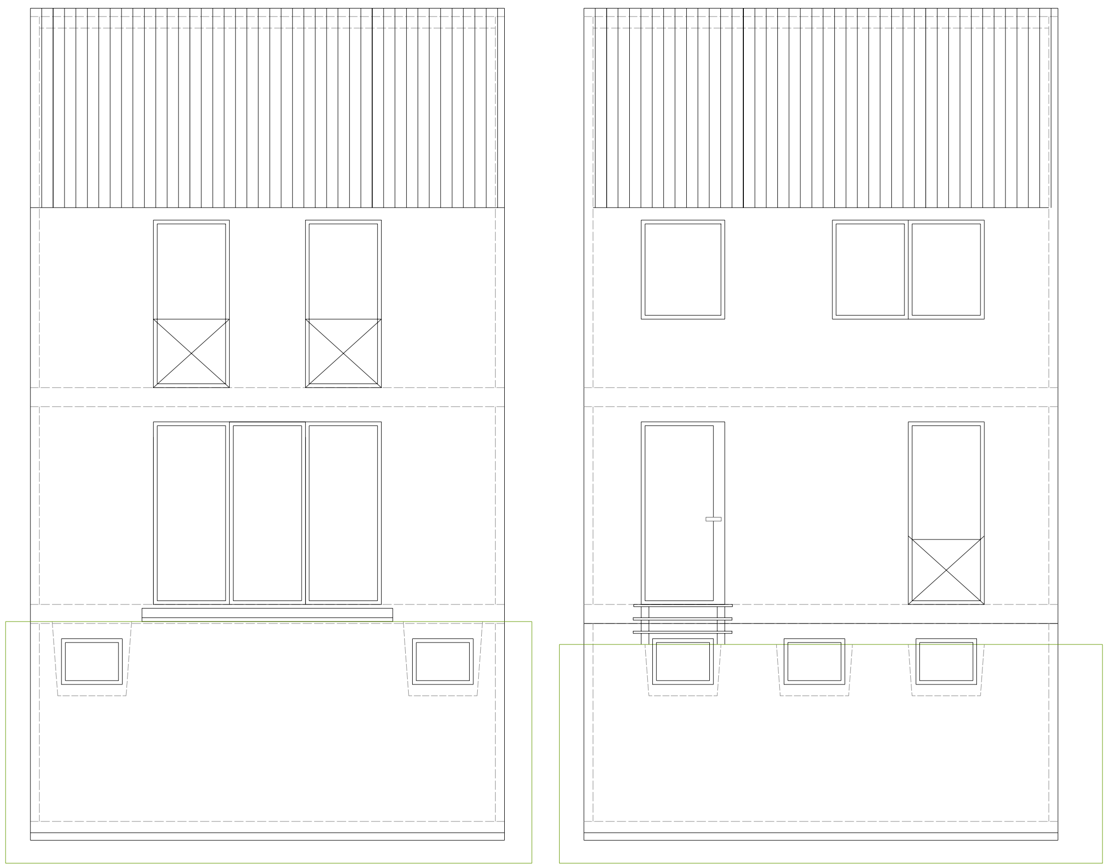
A Documentation of the Example Building used for the Survey on Thermal Insulation

A.1 General Information

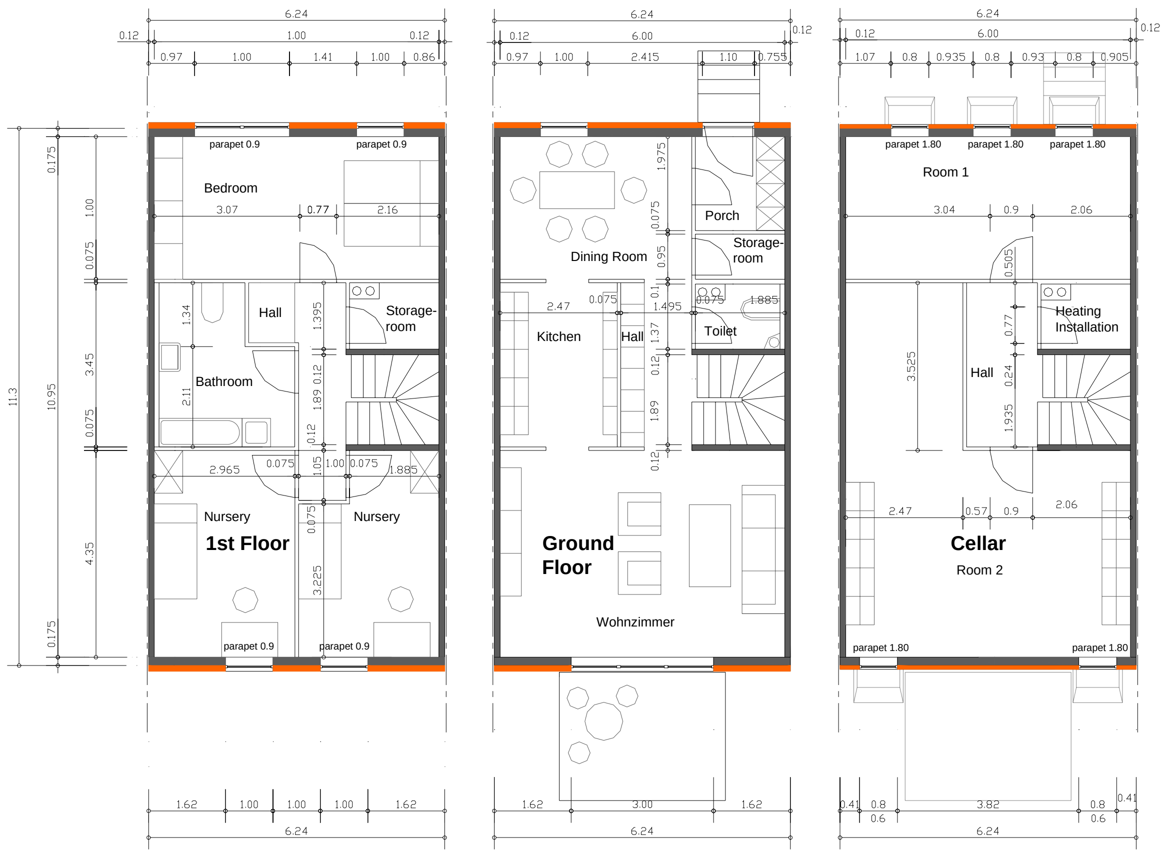
The simulation calculations were carried out for a model of a two-storey end-of-terrace house with basement. The illustrations in the following sections show drawings and the zoning as it was used for the simulation. The ground floor holds an open living, dining, and cooking area plus a toilet. In the first floor, there are a slightly larger bathroom, two living rooms facing to the south, and a somewhat larger room to the north. The basement is divided into two cellar rooms facing north and south and another boiler room.

To the west, there is the terrace's gable wall, to the east adjoins the next housing unit.

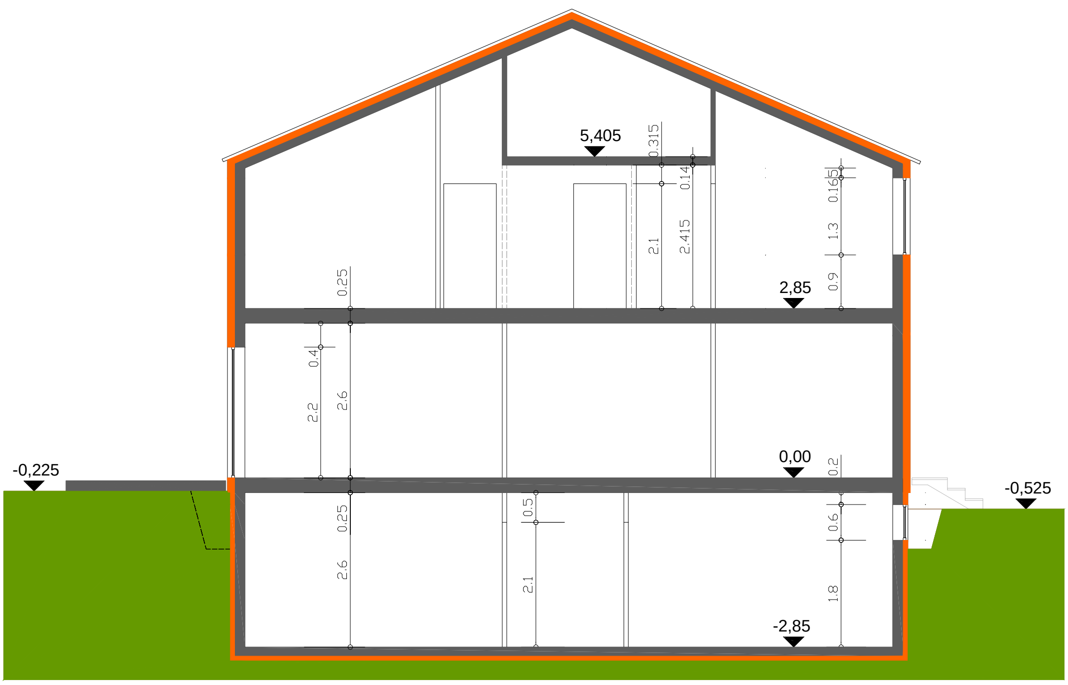
A.2 View from South (left) and North (right)



A.3 Floor plans



A.4 Cross-Sectional View from East



A.5 Zoning

A.6 Structural Elements

The building is put up as a solid construction. North of the Alps, the roof is assembled as a conventional lightweight construction with rafters. Due to local building standards, a solid roof construction was used for the locations of Seville and Rome. The constructional systems of opaque structural elements are summarised in the following.

Cellar wall facing soil				
U-value of a non-insulated structural element [W/(m²K)]			4	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
BASF Styrodur 3035 CS	0-30	33	1.5	0.032-0.04
Standard concrete	17.5	2400	1.08	2.1

Exterior wall				
U-value of a minimally insulated structural element [W/(m²K)]			1.16	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Exterior plaster	1.5	1800	1.08	0.8
EPS-EIFS Neopor	0-30	18	1.21	0.032
Brick masonry	36.5	1400	0.836	0.58
Gypsum plaster EN 12524	1.5	1000	1	0.35

Interior wall				
U-value of structural element [W/(m²K)]			1.6	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Gypsum plaster EN 12524	1.5	1000	1	0.4
Brick masonry	17.5	1400	0.836	0.58
Gypsum plaster EN 12524	1.5	1000	1	0.4

Suspended ceiling				
U-value of structural element [W/(m²K)]			0.89	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Gypsum plaster EN 12524	1.5	1000	1	0.4
Standard concrete	25	2400	1.08	2.1
Impact sound insulation*	2.5	45	0.504	0.045
Coniferous wood	2	415	2.72	0.13

* No impact sound insulation is used for the minimally insulated building.

Roof, solid				
U-value of a minimally insulated structural element [W/(m²K)]			1.0	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Concrete roofing tile	4	2100	1	1.5
Air layer, horizontal	2	42	0.272	0.12
Elastopor H	0-30	30	1.5	0.023
Styropor	2	15	1.21	0.038
Standard concrete	14	2400	1.08	2.1
Gypsum plaster EN 12524	1.5	1000	1	0.4

Roof, lightweight				
U-value of a minimally insulated structural element [W/(m²K)]			0.84	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Concrete roofing tile	4	2100	1	1.5
Air layer, horizontal	2	42	0.272	0.12
Elastopor H	0-30	30	1.5	0.023
Chipboard	1.3	600	1.98	0.13
Air layer (10% rafter)	9	42	0.272	0.452
Rafter with insulation	2.5	82	0.415	0.05
Gypsum wall board 750	1.5	750	1	0.35

Unit's partition wall				
U-value of structural element [W/(m²K)]			0.53	
Material	Thickness d [cm]	Density ρ [kg/m³]	Heat capacity C [kJ/(kgK)]	Thermal conductivity λ [W/(mK)]
Standard concrete	12	2400	1.08	2.1
Sound insulation	6	45	0.504	0.04
Standard concrete	12	2400	1.08	2.1

Depending on insulation standard and climatic zone, different windows are installed. Details are provided in the results overviews in section 3.4. The window is mounted into the thermal insulation layer, as long as its thickness allows doing so. Therefore $\Psi_{installation}$ is in the range of 0.1 W/(mK) for non-insulated walls and 0.01 W/(mK) for a thermal insulation material thickness greater than 10 cm.

The exterior wall surfaces are plastered, the absorbtance for solar radiation is $\alpha = 0.6$. The roof is done in dark clay tiles, with $\alpha = 0.72$.

A.7 Ventilation

The type of ventilation depends on the building standard. In the non-insulated building there is no ventilation system installed, the building is ventilated via the windows only. The objects with improved thermal insulation feature a ventilation system. It ensures, based on the room's volume (zone 1-6), an air change of 0.25. The best thermal insulation standard has additionally a high-performance heat recovery installed which exploits the exhaust air stream (south of the Alps only in connection with air-conditioning).

In addition to the mechanical air change there is infiltration, the building's airtightness is depending on the building standard.

The interior doors from the stairwell to the adjacent rooms (zones 1, 4, 5, 6) are opened only on occasion. On average, these doors allow for an air change of 50 m³/h.

For summertime it is assumed that additional heat removal is achieved by opening the windows. Here the air change depends on the temperature difference between inside and outside, cross-ventilation and wind influence are not considered. In zones 1, 4, and 5, windows are tilted if operative temperatures are above 22 °C and ambient air temperature is lower than indoors. South of the Alps, and where no active air-conditioning is available, it is also possible to ventilate with widely opened windows. Thus, the attainable air change increases by a factor of 10. In the latter case, air change is limited to a maximum of 8 h^{-1}.

A.8 Heating and Cooling

Every room can be heated individually. Heat supply is completely convective and controlled in a way that the operative temperature (i.e. the mean value of air and radiant temperature indoors) just corresponds to the target temperature (here: 20 °C).

For summer comfort, two cases were investigated respectively: In the first case, no active cooling is available. The building is kept cool by proper opening of windows only (cf. above).

In the second case, the larger living rooms, i.e. zones 1, 4, 5, and 6, can be cooled actively. Here an ideal cooling which keeps air temperature to a set value of 25 °C is assumed.

A.9 Internal Heat Gains

It is presumed that no efforts to improve energy efficiency of household appliances, lighting, etc. were undertaken. Therefore, internal heat gains average to 3.0 W/m² for the simulation calculations. Relevant heat gains occur in zone 1 (living) from 7 to 22 o'clock, zone 4 (children) during both day and night time, and zone 5 (bedroom) between 22 to 7 o'clock.

Furthermore, heat output arises from the boiler, hot water tank, and ducts inside the boiler room. They depend on the size of the required heat supply system and are in the range of 60 to 120 W.

A.10 Shading

The example building is oriented exactly in north-south direction. On the south-facing terrace on the ground floor, there is a 2 m wide screen wall. It is installed sideways and facing towards the neighbours. The next row of houses in the south is located in a distance of 23 m.

Whenever it is still conformable with summer comfort, one will often abandon external shading for reasons of economy. Consequently, external shading was omitted for the 4 northern climates. However, in the two southern climates there are traditional shutters installed which will be closed at indoor temperatures above 23 to 25 °C.

B Climate

For Germany, the test reference years, published in 2004 by the German meteorological service [DWD 2004], were available. The test reference year 12 which is assigned to the location of Frankfurt was used.

For the other locations the International Weather for Energy Calculations [IWEC 2001], published by ASHRAE, could be employed. The ASHRAE-CD contained the respective data for all of the 5 different locations.

C Energy Demand and Emssions

The heating system has an efficiency of 0.91, the COP of the cooling system is 3.2. Following DIN 4701-10, the auxiliary energy was taken into account by determining a share which depends on the heating load and the duration of the heating period. Typically, it amounts to some percent of the space heat demand.

The building services systems were accounted for by means of flat efficiency factors (the ratio between space heat demand and heating energy demand, cf. section 3.1, analogous for cooling). The examined example buildings are heated by a low temperature gas boiler. In addition there is the auxiliary electricity demand, calculated from the electricity consumption of the heating circulation pump (here: constantly 35 W) and auxiliary electricity consumption of the boiler. Following [PHPP 2004], the latter was calculated by

$$P_{aux} = 15\,W \cdot \left(\frac{P_{boiler}}{1\,kW} \right)^{0,48} .$$

In doing so, it was assumed that nominal boiler power P_{boiler} exceeds the necessary building heating power by 30%.

The following primary energy and CO_2 factors were used:

	Primary energy factor [$kWh_{Primary}/kWh_{End}$]	CO_2 equivalent factor [kg/kWh_{End}]
Heating (gas)	1.1	0.25
Electricity	2.7	0.68

D Properties of Micronal® PCM

The basis for modelling the PCM-containing material is measurements for a latent heat storage plaster carried out by the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg, Germany [Schossig 2005]. Figure 4 shows the change in heat capacity versus temperature.

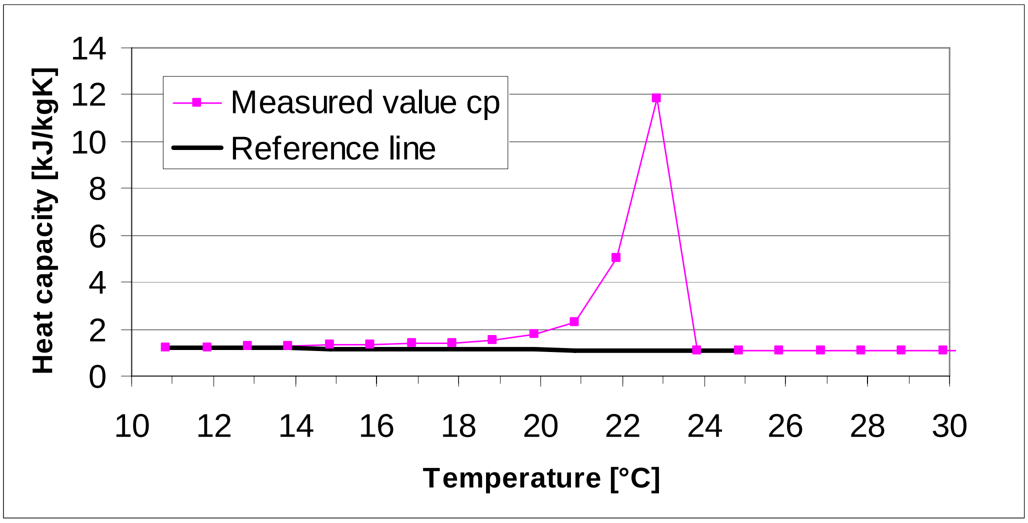


Figure 4: Heat capacity as a function of temperature for the latent heat storage plaster maxit clima 24. Measurements by ISE.

The shown melting curve refers to the product maxit clima 24. The graph reveals that it has a relatively large melting range. Thus, melting enthalpy is defined as follows: One identifies beginning and end of the melting range and draws, as seen in the graph, a line between those two points. The area, enclosed by the line and the graph of measured heat capacity, represents the melting enthalpy.

For the measured data at hand the plaster's enthalpy is 18 kJ/kg within the temperature range of 10.85 °C to 24.85 °C. Here more than 90% of the melting enthalpy is located in a temperature range of 4 K, i.e. approximately between 20 and 24 °C.

From the properties of the set plaster and along with the above data, it was possible to calculate the melting enthalpy for the pure PCM-material in this particular sample, being 100 kJ/kg. According to BASF [Schmidt 2006], the most often measured value is 110 kJ/kg. The acquired measured values for the PCM-material have been adjusted accordingly and converted to the properties of the gypsum plasterboard Micronal® PCM SmartBoard™.

According to the ISE, the curve in the diagram is about 1.5 K higher for the product maxit clima 26. This displaced curve was used in the survey at hand, since the melting point of 24 °C is more appealing for summertime thermal protection. For the simulations, the curve was divided into five different sections. In each section, the heat capacity was assumed to be constant.