Accuracy of Energy Analysis of Buildings: A Comparison of a Monthly Energy Balance Method and Simulation Methods in Calculating the Energy Consumption and the Effect of Thermal Mass

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(Received 7 October 2007)

ABSTRACT: The purpose of this article is to analyze the effects of thermal mass on heating and cooling energy in Nordic climate and for modern, well-insulated Nordic buildings. The effect of thermal mass is analyzed by calculations made by seven researchers and by seven different calculation programs. Six of these programs are simulation programs (Consolis Energy, IDA-ICE, SciaQPro, TASE, VIP, VTT House model) and one monthly energy balance method (maxit energy) based on the standard EN 832, which is the predecessor of ISO DIS 13790. It is purpose to evaluate the reliability of the monthly energy calculation method and especially its gain utilization factor compared with the simulation programs. In addition some sensitivity analysis concerning e.g., the effects of the size and the orientation of windows and the weather data on the energy consumption are made.The results show that the simplified standard methods of EN 832 and of ISO DIS 13790 generally give accurate results in calculating the annual heating energy, e.g., in the context of energy design and energy certification. However, the gain utilization factor of these standards is too low for very light buildings having no massive surfaces resulting in a too high energy consumption. The study shows, that the differences in input data cause often greater differences in calculation results than the differences between various calculation and simulation methods.

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Figures 1–16 appear in color online: http://jen.sagepub.com

1744-2591/08/02 0101–30 $10.00/0 DOI: 10.1177/1744259108093920

Los Angeles, London, New Delhi and Singapore

KEY WORDS: buildings, energy consumption, thermal mass, heat capacity, simulation, monthly calculation, utilization factor.

INTRODUCTION

THE THERMAL MASS, or exactly the heat capacity, of buildings affects heating and cooling energy and indoor temperatures. Its effects have been studied since the 1980's when the first energy analysis methods were developed (e.g., Jóhannesson, 1981). The effects of thermal mass on energy consumption and indoor temperatures can be easiest analyzed using calculations. It would be extremely tedious and expensive to analyze its effects using measurements. However, such measurements have been made (e.g., Kalema and Martikainen, 1987; and Lindberg et al., 2004). The problem in these measurements is to assure, that the conditions in the buildings to be studied really are fully comparable, when small differences due to the thermal mass are measured. When using calculations it is important to try to ascertain that the calculation methods used are reliable. This can be done e.g., by using many calculation models based on different methods.

In Southern-Europe the interest on thermal mass has mainly been in the cooling energy. The effect of thermal mass is relatively clearly greater in cooling energy than in heating energy. This is due to the fact that in cooling the variation of load is mainly diurnal and this can be effectively smoothened with a great thermal capacity. In heating the variation of load is mainly annual. Therefore, the effects of thermal mass on cooling energy have been studied much more than those in heating energy. C. A. Balaras (1996) has e.g., made a general analysis of the role of thermal mass on cooling energy and the methods suitable for analysis.

In Nordic countries, such as Finland, the interests on the advantageous effects of thermal mass have partly changed with time. Earlier the main question of research was what the effect of thermal mass on heating energy is. The improvement of building's thermal insulation and the use of heat recovery from exhaust air have noticeably reduced heat losses of buildings. On the other hand the increasing use of household electricity and the use of big window areas on south facades have increased internal heat gains. For these reasons the internal temperatures of buildings during spring and summer can rise high and cause a ventilating or a cooling need. Therefore, a new research question also in Nordic countries is, what is the effect of thermal mass on internal temperatures and on cooling energy. The rapid increase of air-to-air heat pumps, which can be used for cooling in summertime, has also increased in practice their use for cooling in Finland.

For these reasons some literature analysis on this subject has been done (Hietamäki et al., 2003).

When talking on the accuracy of calculations there are two different issues. The first one is the question on how accurately the simulation program used can calculate the effect of certain physical phenomena, e.g., that of the thermal mass. The other and a more difficult question is how accurately the absolute energy consumption of a certain building can be calculated. This is an important question for the future, when buildings' energy performance requirements are set in absolute numbers, e.g., as a certain energy consumption/floor area.

The accuracy of the calculation of buildings' energy consumption is a much studied issue. It has been studied e.g., in the Annexes and Tasks of International Energy Agency (e.g., Lomas et al., 1994, 1997). The general result from theses studies is that the effects of certain physical phenomena on energy consumption can be calculated quite accurately, but the calculation of the absolute (real) energy consumption is unsure.

There are in principle two levels in the energy analysis of buildings. It can be used thermal simulation programs or calculation methods based on a monthly energy balance. A simulation program here means a program which uses a short time-step in calculations (typically 1 h) and which calculates at the same time heating and cooling needs and the interior temperature. There are many buildings' thermal simulation programs having different principles and complexity e.g., in calculating convection, radiation and transient conduction. Six simulation programs was used in this study.

An energy balance method calculates only monthly heating and cooling needs. From these the perhaps best known method is the standard proposal ISO DIS 13 790, *Thermal Performance of Buildings – Calculation of Energy Use for Space Heating and Cooling (2005)*. This is a modification and an addition to the standard EN 832 (1998) *Thermal Performance of Buildings – Calculation of Energy Use for Space Heating*. The latest version of ISO DIS 13790 also includes a calculation method for monthly cooling energy and a simplified hourly calculation method for heating and cooling energy.

The role of buildings' energy analysis using calculations is coming more important also due to new regulations. *The directive on the energy performance of buildings* (EPBD, 2002) demands, that the energy performance (e.g., energy consumption/floor area) must be calculated for new buildings in the design phase. EPBD also demands the use of an energy certificate for buildings, when they are sold or rented. This certificate is based for new buildings on calculations. It is naturally important that these calculations are made in an accurate way.

The accuracy of energy calculations depends on three issues:

1. On the skills of the modeler to describe the reality into a calculation model
2. On the reliability of physical input data (e.g., dimensions of surfaces, values of materials' thermal properties, heat transfer coefficients) and
3. On the calculation method used.

The first two issues are not handled here. It is clear that the more skilled and experienced the modeler is and the more reliable input data is obtainable the more reliable results he/she can obtain. However, it is interesting to find out if more complex analysis methods give more accurate results and if there are faults in the simplifications used in the monthly calculation method. e.g., the correctness of the gain utilization factor of ISO DIS 13 790 has been questioned sometimes, partly therefore that its origin and background is unclear.

The results of this study are based on the research Kalema et al. (2006). This was a joint Nordic research, which was financed by the building material industry. There were involved researchers from Finland, Sweden and Norway from two universities (Tampere University of Technology and Kungliga Tekniska Högskolan), two research institutes (VTT and Sintef) and three companies (maxit energy Ab, Cementa Ab and Ax-Consulting Oy). Six thermal simulation programs (Consolis Energy, IDA Climate and Energy, SciaQpro, VIP, VTT House model and TASE) and one monthly energy balance method (maxit energy based on EN 832) were used (Table 1). From the six simulation programs Consolis Energy and VIP are less complex than the four other.

This study had two main goals. First purpose was to make a comprehensive study on the effects of thermal mass on heating and cooling energy in Nordic climate for typical, modern Nordic buildings. The second purpose was to evaluate the reliability of the monthly calculation method based on standards EN 832/ISO DIS 13790 and especially the correctness of the utilization factor for internal heat gains. In addition, it was performed sensitivity analysis concerning the effects of the size and the orientation of windows and the weather data on energy consumption.

UTILIZATION FACTOR FOR HEAT GAINS

The role of the standard ISO DIS 13 790 is becoming important in Europe, because it has been taken into use in many countries as an official method, which is used in the energy analysis made for new buildings according to *The directive on the energy performance of buildings*. Therefore, it is interesting and important to know its accuracy and capability in analyzing modern,

Table 1. Energy calculation programs and their users in this study.

Program	User/Country	Description of program	Reference
Consolis energy	KTH, Sweden	Two-zone model, simplified thermal dynamics	Jòhannesson (2005)
Ida climate and energy	Ax-Consulting Oy, Finland	Thermal, multi-zone simulation model	IDA (2006)
SciaQPro	Sintef, Norway	Thermal, multi-zone simulation model	Kalema et al. (2006)
TASE	TUT, Finland	Thermal, multi-zone simulation model	Aittomäki and Kalema (1976) Kalema (1992)
VIP	Cementa AB, Sweden	Simplified dynamic method, single-zone model*	VIP+ (2002)
VTT house model	VTT, Finland	Thermal, multi-zone simulation model	Tuomaala (2002)
Maxit energy	Maxit Oy Ab, Finland Control Engineering Ab, Sweden	Monthly energy balance method, single-zone calculation	Maxit energy (2006)

*Now also available as a multi-zone model.

well-insulated buildings. The central idea in ISO DIS 13 790 is to take into account the useful part of internal and solar heat gains in the energy need for heating by using *the gain utilization factor*. Correspondingly the useful heat loss can be taken into account in the energy need for cooling by using *the loss utilization factor*. The utilization factor is a correlation equation based on thermal simulations. It has been studied e.g., in the PASSYS project (1989). However, its exact background is ambiguous.

We have compared in this study two forms of gain utilization factors; those of EN 832 and ISO DIS 13 790 (Equations 3 and 4) and those presented by van Dijk and Arkestejn (1987) (Equation 13). Yohanis and Norton (1999) have studied the validity of the coefficients of K and D of Equation 13. They get in their analysis coefficients that give a slightly lower gain utilization factor (6–14% lower for the gain/loss ratio 1) than that of van Dijk and Arkestejn for three classes of thermal mass (light, heavy, and very heavy). The smaller utilization factor of Yohonis and Norton is probably due to the detailed zoning. They used in their office building a 14 – zone model. They also point out that the utilization factor determined on a whole-building basis may lead to significant errors.

The goal of science is to create general laws and specifically that of engineering general design methods. The basic equation of ISO DIS 13 790 (Equation 1) is such. It has no limitations concerning e.g., the weather or the building type. Therefore, the idea, which Jokisalo and Kurnitski (2005, 2007) present, that each building and climate should have their own individual calculation equations (in this case the parameters a_0 and τ_0 in Equation 11) would lead to a loosing of the general calculation model. For calculating the annual energy consumption of a building for certain weather and for certain building type, these two parameters should be at first determined.

The values of the parameters mentioned above are in ISO DIS 13 790 $a_0 = 1.0$ and $\tau_0 = 15\,\text{h}$. Jokisalo and Kurnitski (2007) get for the adjusted coefficients for Finnish climate the following values: apartment buildings $a_0 = 6$ and $\tau_0 = 7\,\text{h}$ and office buildings $a_0 = 2$ and $\tau_0 = 15\,\text{h}$.

Another problem with the improved coefficients of Jokisalo and Kurnitski is that they are based on the calculation results of a single simulation model (IDA Indoor Climate and Energy, 2006), which is considered as a physical truth. In our calculations IDA ICE gave approximate a 6% lower heating energy need for the single-family house than the average need of all programs. A possible wrong value in the calculated heating energy need affects directly in Equation 14 on the utilization factor.

Parameters $a_0 = 1.0$ and $\tau_0 = 15\,\text{h}$ of ISO DIS 13 790 are the same both in the calculation of monthly heating energy using the gain utilization factor as well as in that of monthly cooling energy using the loss utilization factor. Therefore from the point of view of our study the results of Corrado and

Fabrizio (2006, 2007) concerning the parameters of the loss utilization factor are interesting. They have studied the validity of the loss utilization factor for cooling for Italian climate and building stock. They come to the conclusion, that the loss utilization factor for cooling is correct in its general expression, but they propose parameters $a_0 = 6.3$ and $\tau_0 = 17\,\mathrm{h}$. They came to the conclusion that ISO DIS 13790 is capable to calculate the annual cooling energy of buildings provided the dynamic parameters (a_0 and τ_0) are correct.

The gain utilization factor for heating (subscript H) is defined by Equation 1 and the loss utilization factor for cooling (subscript C) by Equation 2:

$$Q_{\mathrm{NH}} = Q_{\mathrm{LH}} - \eta_{\mathrm{GH}} Q_{\mathrm{GH}} \tag{1}$$

$$Q_{\mathrm{NC}} = Q_{\mathrm{GC}} - \eta_{\mathrm{LG}} Q_{\mathrm{LC}} \tag{2}$$

where

Q_{N} is monthly energy need (H heating, C cooling)

Q_{L} monthly heat loss

Q_{G} monthly heat gain (internal and solar gains)

η_{G} monthly gain utilization factor for heating

η_{L} monthly loss utilization factor for cooling

The standard proposal *ISO DIS 13790* gives for the gain utilization factor for heating (η_{GH}) two equations as a function of the gain/loss ratio (γ_{GH}) (Equations 3 and 4). Correspondingly, for the loss utilization factor for cooling η_{LC} Equations 5 and 6 are given as a function of the loss/gain ratio λ_{LC}. Equations (4) and (6) are for the special case when the gain/loss ratio is exactly 1:

$$\text{if } \gamma_{\mathrm{GH}} \neq 1: \quad \eta_{\mathrm{GH}} = \frac{1 - \gamma_{\mathrm{GH}}^{a_{\mathrm{H}}}}{1 - \gamma_{\mathrm{GH}}^{a_{\mathrm{H}}+1}} \tag{3}$$

$$\text{if } \gamma_{\mathrm{GH}} = 1: \quad \eta_{\mathrm{GH}} = \frac{a_{\mathrm{H}}}{a_{\mathrm{H}} + 1} \tag{4}$$

$$\text{if } \lambda_{\mathrm{LC}} \neq 1: \quad \eta_{\mathrm{LC}} = \frac{1 - \lambda_{\mathrm{LC}}^{a_{\mathrm{C}}}}{1 - \lambda_{\mathrm{LC}}^{a_{\mathrm{C}}+1}} \tag{5}$$

$$\text{if } \lambda_{\mathrm{LC}} = 1: \quad \eta_{\mathrm{LC}} = \frac{a_{\mathrm{C}}}{a_{\mathrm{C}} + 1} \tag{6}$$

The gain utilization factor for heating (γ_{GH}) and the loss utilization factor for cooling (λ_{LC}) are calculated from Equations (7) and (8):

$$\gamma_{\mathrm{GH}} = \frac{Q_{\mathrm{GH}}}{Q_{\mathrm{LH}}} \tag{7}$$

$$\lambda_{\mathrm{LC}} = \frac{Q_{\mathrm{LC}}}{Q_{\mathrm{GC}}} \tag{8}$$

The total heat loss is the sum of transmission (Q_T) and ventilation heat losses (Q_V)

$$Q_L = Q_T + Q_V \tag{9}$$

The total amount of heat sources (Q_G) consist from the internal heat sources (such as lighting and heat from appliances and persons, Q_i) and from the solar heat sources (Q_S), which mainly consist from the solar radiation transmitted trough windows:

$$Q_G = Q_i + Q_S \tag{10}$$

The dimensionless parameters a_H and a_C in Equations 3–6 are calculated from Equation (11), which is the same for heating and for cooling:

$$a = a_H = a_C = a_0 + \frac{\tau}{\tau_0} \tag{11}$$

where
a_0 is a parameter, which is $a_0 = 1.0$ for continuously heated buildings and for monthly calculations
τ_0 reference time constant, which is $\tau_0 = 15\,\text{h}$ for continuously heated buildings and monthly calculations

The time constant of the building or its zone is

$$\tau_H = \frac{C_m}{H_L} \tag{12}$$

C_m is internal heat capacity of the building or its zone,
H_L heat loss coefficient of the building or its zone.

Also other kind of utilization factors as that of ISO DIS 13 790 have been studied. van Dijk and Arkesteijn (1987) report as a result of the PASSYS project some gain utilization factors. From the equations they have studied the best fit for the gain utilization factor for the cases of our study seems to be obtainable with Equation 13:

$$\eta_{GH} = 1 - e^{-K/(\gamma_{GH} - D)} \tag{13}$$

where the parameters K and D for two building types are presented in Table 2.

When evaluating the validity of the monthly utilization factors of Equations 3, 4 and Equation 13 the reference utilization factors of this study

Table 2. Parameters K and D for Equation (13). Continuous heating (van Dijk and Arkesteijn, 1987).

Building type	*K*	*D*
Masonry type	1.35	0.27
Wooden frame type	1.19	0.00

are calculated monthly from two simulations using Equation 14. Simulation 1 is made using a fixed interior temperature (both the heating and the cooling set point temperatures are 21°C), which gives a heat loss comparable with that of ISO DIS 13 790. Simulation 2 is made using real set-point temperatures (21°C for heating and 25°C for cooling). This calculation gives a real net heating energy. With these two simulations the gain utilization factor is:

$$\eta_{\mathrm{GH}} = \frac{Q_{\mathrm{L1}} - Q_{\mathrm{NH2}}}{Q_{\mathrm{GH}}} \tag{14}$$

where

Q_{L1} is monthly heat loss from simulation 1 calculated at a fixed interior temperature

Q_{NH2} monthly net heating energy from simulation 2

Q_{GH} monthly total heat gain (same in both simulations)

In this study the utilization factors were analyzed using TASE, Consolis Energy and VIP programs.

INPUT DATA OF CALCULATIONS

Calculations are made for a 162 m^2 single-family house (Figure 1) and for a double-zone flat of an apartment building (Figure 2). The flat is a second or a third floor flat of a four-storey building, so that the floor and the ceiling are interior surfaces. The basic model for both building types is a double-zone model, but also single-zone modeling is used. In addition to that the single-family house is also calculated as a 15 room model with the VTT House model.

The basic direction of the exterior facades of the single-family house is east–west. The main windows (45% from the total window area) are facing towards south and the total window area/floor area is 12%. The basic direction of the exterior facade of the double-zone model of the apartment flat is north–south. The main windows (84% from the total window area) are facing towards west and the total window area/floor area is 25%.

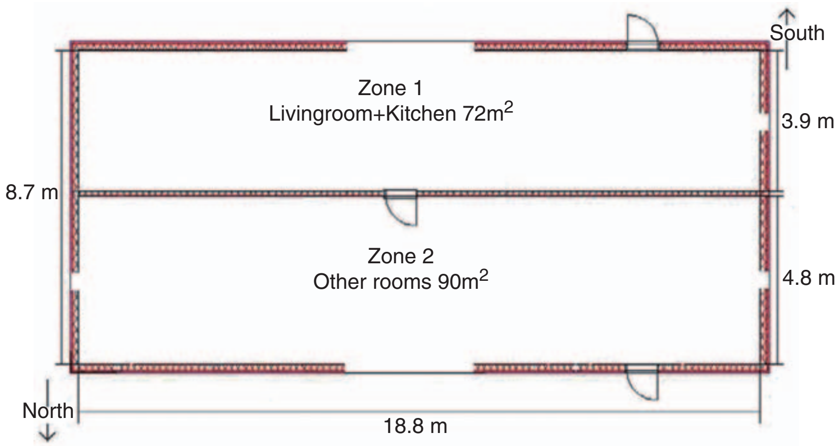

Figure 1. *Single-family house modeled using two zones. Main facades in east–west direction.*

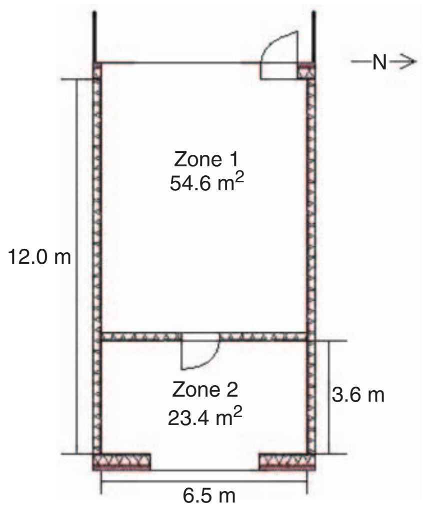

Figure 2. *Two-roomed flat of the apartment building. Facades in north–south direction.*

The single-family house is a ridge roofed building having alternatively four structures; the extra light, the light, the semi-weight and the massive ones (Table 3). Their thermal capacities per floor area are 50–610 kJ/K/m^2 and their time constants 17–210 h, respectively. The extra-light and the light buildings have parquet flooring and the semi-weight and the heavy

Table 3. Thermal capacities and time-constants of the buildings studied.

		Single-family house		Apartment flat	
Structure	**Floor/flooring**	**Heat capacity/ floor-area (kJ/(Km^2))**	**Time constant (h)**	**Heat capacity/ floor-area (kJ/(Km^2))**	**Time constant (h)**
Extra light-weight	Light/parquet	50	17	55	17
Light-weight wooden	Massive/parquet	190	65	–	–
Semi-weight masonry	Massive/Ceramic tile	470	160	–	–
Massive concrete	Massive/Ceramic tile	610	210	1330	410

Table 4. U-values of exterior walls.

	U-value		Both building types	
Structure	**Single-family house (W/(Km^2))**	**Apartment flat (W/(Km^2))**	**Average solar transmission**	**Frame factor**
Wall	0.22	0.23		
Roof	0.13			
Floor	0.13			
Window	1.4	1.4	0.58	0.20
Exterior door	1.4	1.4		

buildings have ceramic tile flooring. In the extra-light building all constructions including the floor are light. In the light building the floor is massive (a 80 mm concrete slab), but other surfaces are light. The U-values of the corresponding components of the exterior envelope (Table 4) are exactly the same for all structures and fulfill the present Finnish building regulations (2003). For the sake of simplicity and unambiguity the floor is assumed to be a ventilated floor, below which exterior temperature prevails.

The apartment flat has two constructions; the extra-light and the massive one. Their thermal capacities and time constants are 55 and 1330 kJ/K/m^2 and 17 and 410 h, respectively. In the extra-light flat all constructions (floor, ceiling, exterior wall and interior walls) are light and in the massive one they are heavy (concrete). Because we have studied only one light apartment flat structure, it is later called simply the light one.

The set point temperature for heating is 21°C and that for mechanical cooling 25°C. Table 5 gives the ventilation air flow rates and the efficiency of the heat recovery system. The internal heat gains of both building types are 5 W/m^2 calculated per floor area on the average. They are 50% convective and 50% radiative. The weather data used is the synthetic weather of Meteonorm for Helsinki (Meteonorm, 2005) (Table 6).

Also in order to avoid unambiguity as far as possible due to different modeling principles in different simulation programs the long-wave radiation and the absorption of solar radiation on exterior walls and roofs is neglected as it also usually is neglected in calculations made by ISO DIS 13 790.

Table 5. Ventilation air flow rates and efficiency of heat recovery.

		Single-family house			Apartment flat		
Quantity	**Unit**	**Zone 1**	**Zone 2**	**House**	**Zone 1**	**Zone 2**	**Flat**
Air flow rate	dm^3/s	29	36	65	32	14	46
Air change rate	1/h			0.58			0.75
Infiltration	1/h			0			0
Efficiency of heat recovery	–	0.50	0.50	0.50	0.30	0.30	0.30
Other		No ventilation between zones			No ventilation between zones		

Table 6. Monthly exterior temperature and solar radiation onto horizontal surface. Meteonorm (2005) for Helsinki.

		Solar radiation on horizontal surface		
Month	**Exterior temperature (°C)**	**Direct (kWh/m^2)**	**Diffuse (kWh/m^2)**	**Total (kWh/m^2)**
1	−6.4	1.8	5.8	7.6
2	−7.0	9.8	14.9	24.7
3	−2.3	26.7	36.9	63.6
4	3.3	49.8	58.2	108.0
5	10.3	89.6	75.3	164.9
6	14.0	102.5	80.6	183.1
7	16.9	91.5	79.9	171.4
8	15.2	58.3	67.4	125.7
9	9.7	28.2	41.7	69.9
10	4.9	13.2	19.2	32.4
11	−0.1	1.9	6.9	8.8
12	−4.5	0.6	3.8	4.4
Year	4.6	474.1	490.7	964.8

RESULTS

Calculated Energy Consumptions and their Inaccuracy

The annual heating energy is calculated within an inaccuracy of 5–8 kWh/m^2 both for the single-family house and for the apartment flat with five simulation programs of our study when the number of zones and the thermal mass are the same correspondingly. From these numbers the results of maxit energy and VTT House model are excluded for reasons explained later. As a relative inaccuracy these numbers are ~10% (Tables 7–9). Also the annual cooling energy of the single-family house is calculated approximately within an inaccuracy of 5 kWh/m^2. However, due to the small cooling energy need this is as a relative inaccuracy ~50%. For the cooling

Table 7. Maximum differences in calculation results of the double-zone case of the single-family house. Calculation results of IDA, Consolis Energy, TASE and SciaQPro.

		Energy		Difference between max and min energy		Programs	
Thermal mass	Energy	Max. (kWh/m^2)	Min. (kWh/m^2)	Absolute (kWh/m^2)	Relative* (%)	Max	Min
Mas	Heating	63.8	58.8	5.0	8	SciaQPro	IDA
Mas	Cooling	7.8	3.5	4.3	55	SciaQPro	IDA
ExL	Heating	66.5	61.2	5.3	8	SciaQPro	IDA
ExL	Cooling	12.5	7.0	5.5	44	SciaQPro	TASE

*Calculated from the greater energy consumption.

Table 8. Maximum differences in calculation results of the single-zone case of the single-family house. Calculation results of IDA, Consolis Energy, TASE, SciaQPro and VIP.

		Energy		Difference between max and min energy		Programs	
Thermal mass	Energy	Max. (kWh/m^2)	Min. (kWh/m^2)	Absolute (kWh/m^2)	Relative* (%)	Max	Min
Mas	Heating	64.2	58.2	6.0	9	SciaQPro	VIP
Mas	Cooling	8.0	3.0	5.0	63	SciaQPro	IDA
ExL	Heating	68.6	60.8	7.8	11	SciaQPro	IDA
ExL	Cooling	11.5	6.0	5.5	48	SciaQPro	IDA

*Calculated from the greater energy consumption.

energy of the double-zoned apartment flat clearly different values are obtained with various programs (Table 9). The difference between the maximum and minimum cooling energy needs is 20–22 kWh/m^2, which correspond a relative difference of nearly 50% (Table 9).

The greatest values both in heating energy as well as in cooling energy are obtained with the 15-zone VTT House model (Figure 3). The most probable reason for this is that in our calculations in the 15-zone model, all interior doors are closed air-tightly. This causes simultaneous heating and cooling,

Table 9. Maximum differences in calculation results of the double-zone case of the apartment flat. Calculation results of Consolis Energy, TASE and SciaQPro.

Thermal mass	Energy	Energy Max. (kWh/m^2)	Energy Min. (kWh/m^2)	Difference between max and min energy: Absolute (kWh/m^2)	Difference between max and min energy: Relative* (%)	Programs Max	Programs Min
Mas	Heating	68.2	63.0	5.2	8	Consolis	TASE
Mas	Cooling	42.0	22.0	20.0	48	SciaQPro	TASE
ExL	Heating	71.8	66.0	5.8	8	SciaQPro	TASE
ExL	Cooling	49.5	28.0	21.5	44	SciaQPro	TASE

*Calculated from the greater energy consumption.

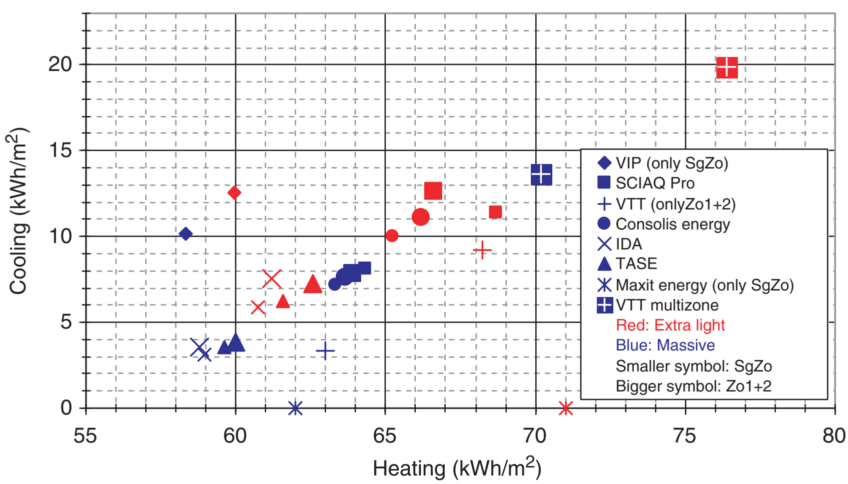

Figure 3. *Annual heating and cooling energy for the basic case of the single-family house. Single-zone (SgZo), double-zone (Zo1+2), and 15-zone (MulZone) cases. Maxit energy calculates only heating energy.*

which increase at the same time both heating and cooling energy needs. This can be deduced e.g., from the fact, that the results calculated for a comparison with a two-zone VTT House model were relatively close to the results of the other simulation programs. One conclusion from this is that a too detailed modeling does not necessarily give reasonable and correct results compared with the reality if the modeling includes unreliable assumptions.

Maxit energy, which is a monthly energy calculation method based on standards EN 832/ISO DIS 13 790, gives a too high heating energy for the extra-light building due to an error in the utilization factor. This issue is discussed in detail later in the text.

Compared with the results of the single-family house the need for cooling energy in the apartment flat is relatively noticeable higher than that for heating energy (Figures 3 and 4). In the apartment flat cooling energy is ~50% from heating energy when it is in the single-family house only approximately 10%.

The total spread in the calculated values of energy need is high, when all calculation results are compared with each other (Figures 3 and 4). The spread in heating energy is 58–76 k Wh/m^2 for the single-family house and 55–72 k Wh/m^2 for the double-zone apartment flat. The corresponding values for the cooling energy are 3–20 k Wh/m^2 and 16–50 k Wh/m^2. These numbers include the results of all programs used, the extra-light and the heavy constructions and the single-zone and double-zone models.

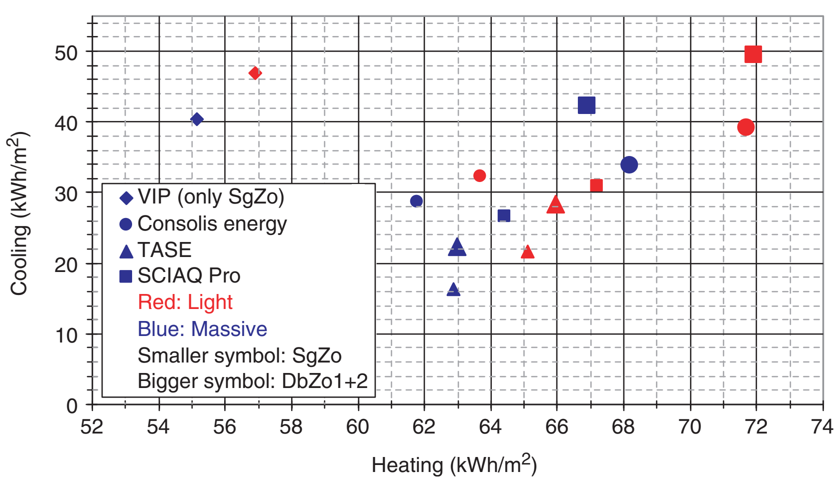

Figure 4. *Annual heating and cooling energy for the apartment flat. Single-zone (SgZo) and double-zone (Zo1+2) cases.*

The spread of results is considerably smaller, when only exactly the same cases concerning the thermal mass and the number of zones are compared with each other and the not comparable results (VTT House model, maxit energy) are excluded (Tables 7–9).

The directive on the energy performance of buildings demands that the energy consumption of a building to be designed must be calculated. If the energy performance criteria is set as a numeric value (e.g., 80 k Wh/m^2 for space heating) very different technical solutions may meet this requirement, if the calculation method and the details of modeling are not defined accurately enough. Especially it seems that the calculated need for cooling energy can include great uncertainties. On the other hand, such a simple energy balance method as ISO DIS 13 790, gives reliable results for heating energy, when the error included in the energy need of the extra-light buildings is taken into account.

Effect of Thermal Mass

The effect of thermal mass on heating and cooling energy depends on many physical things, e.g., the internal heat gains, the solar radiation trough windows, the weather data, the level of thermal insulation of the envelope and the ventilation air flow rates and the type of the building affect the energy consumption and the question, what the effect of thermal mass is. Naturally the effect which for the thermal mass is obtained depends on the calculation model used and the number of zones in it.

The effect of thermal mass in a Nordic climate (weather data of Helsinki, for which the average exterior temperature is 4.6 °C and the total solar radiation on a horizontal surface is 965 kWh/m^2) is approximately in heating energy 3 kWh/m^2 and in cooling energy 4 kWh/m^2 when the double-zone models of TASE, Consolis Energy and SciaQPro are used in the analysis and the extra-light and the massive single-family houses are compared with each other (Figures 3–6 and Table 10). TASE and Consolis Energy give approximately the same effect for the thermal mass and SciaQPro a slightly higher effect for the thermal mass in cooling energy. All programs give for the effect of thermal mass in cooling energy a slightly higher value for the apartment flat than for the single-family house.

The thermal mass clearly decreases energy consumption, when its value is increased from the value 50 kJ/K/m^2 (extra-light building) to the value 470 kJ/K/m^2 (semi-weight building). The corresponding time-constants are $\sim$20 h and 160 h. When increasing the thermal mass from the level of the semi-weight building the energy saving obtainable due to the additional thermal mass is very small (Figure 5).

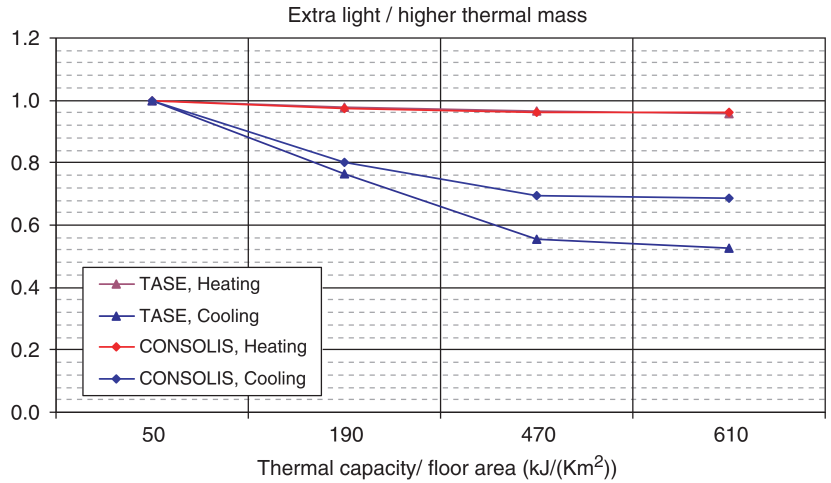

Figure 5. *Effect of thermal mass on the annual heating and cooling energy. Single-family house, a double-zone model.*

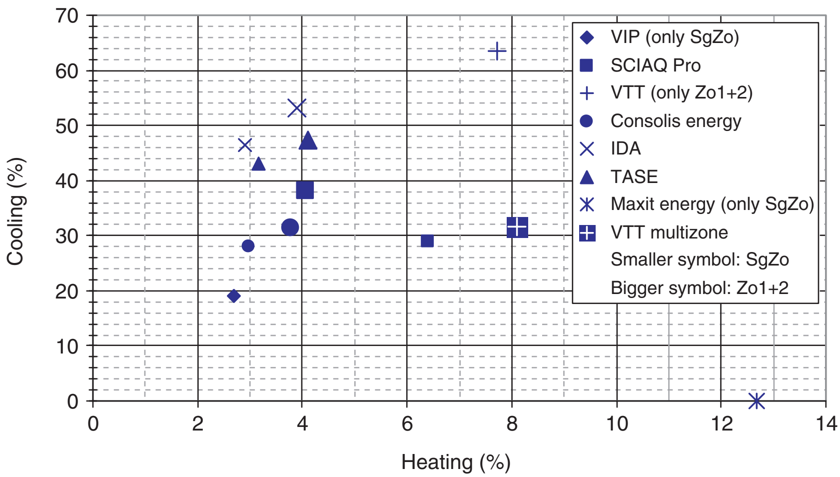

Figure 6. *Relative difference in the needs for annual heating and cooling energy between the extra-light and the massive single-family houses using various simulation programs and single-zone and double-zone models.*

For the basic orientation of windows of the apartment flat (main window area is towards west) the effect of thermal mass is approximately the same as that in the single-family house. The difference in the energy consumptions between the extra-light and the massive flat is

Table 10. Decrease of energy consumption when building's thermal mass is changed from the extra-light to massive. Double-zone models.

Type of building	Program	Energy	Change in energy need (kWh/m^2)	(%)
Single-family house	Tase	Heating	2.5	4.0
	Tase	Cooling	3.5	47
	Consolis	Heating	2.5	3.8
	Consolis	Cooling	3.5	32
	ScaiQPro	Heating	2.5	3.8
	ScaiQPro	Cooling	4.5	36
Apartment flat	Tase	Heating	3.0	4.5
	Tase	Cooling	6.0	21
	Consolis	Heating	3.5	4.9
	Consolis	Cooling	5.0	13
	ScaiQPro	Heating	5.0	6.9
	ScaiQPro	Cooling	8.0	16

approximately 3 k Wh/m^2 in heating energy and 5 k Wh/m^2 in cooling energy (Table 10).

The effect of thermal mass on heating and cooling energy strongly depends on the windows' area and orientation. The effect of thermal mass clearly increases, when the windows' size is increased on the south façade. When the effect of thermal mass is about 5% in heating energy for the basic size of windows (12% from the floor area), this effect is ~10% for the window size of 20% from the floor area and 15% for the window size of 45% from the floor area, when the extra-light and the massive single-family houses are compared with each other and when the window size is increased on the south façade (Figures 7 and 8).

If for the apartment flat the basic orientation of windows (84% from the total window area is facing towards west) is changed so that the main window area is facing towards south the effect of the thermal mass approximately is in heating energy 10 k Wh/m^2 and in cooling energy 14 k Wh/m^2, when the double-zone flat of TASE is used in the analysis and the extra-light and the massive constructions are compared with each other. Relatively this effect is ~15% in heating energy and 35% in cooling energy.

Maxit energy, which is based on the standards EN 832/ISO DIS 13 790, gives for the effect of thermal mass in heating energy 9 k Wh/m^2 (13%), when the massive and the extra-light single-family houses are compared with each other (Figure 6). This great effect is due to the

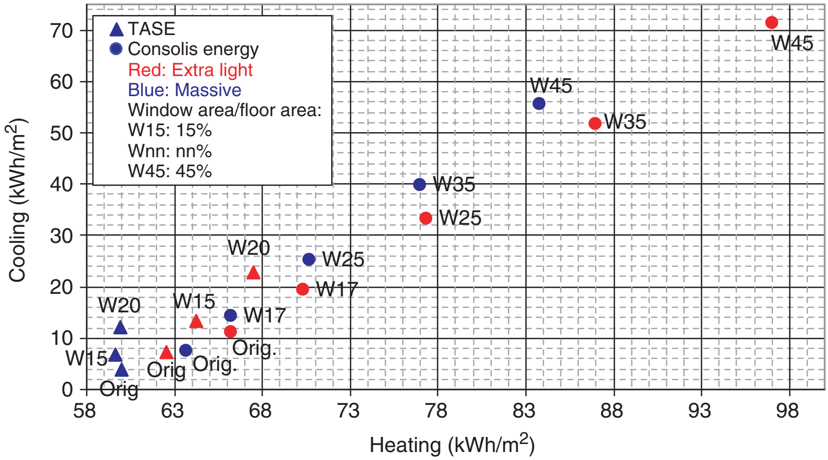

Figure 7. *Effect of windows' orientation and size on the annual heating and cooling energy. Double-zone, single-family house.*

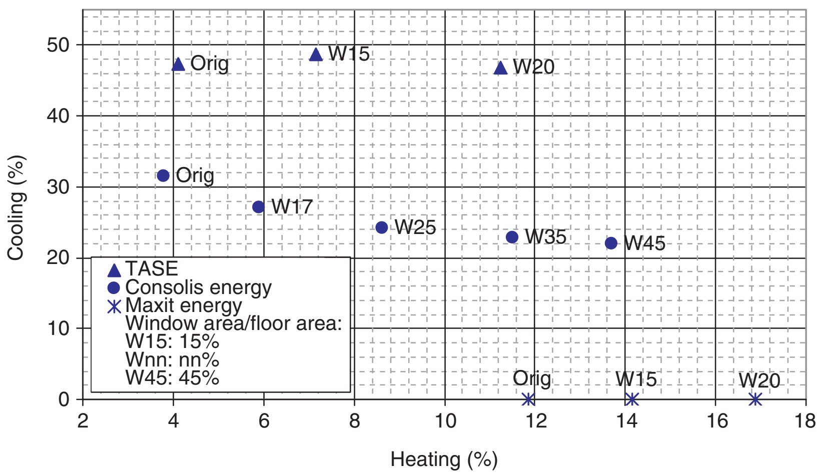

Figure 8. *Effect of windows' size on the relative difference between the needs for annual heating and cooling energy of the extra-light and the massive single-family houses. Single-zone building in maxit energy, in others double-zone building. Basic window area 12% from the floor area.*

problem (error) in the utilization factor of the extra-light building, which is discussed later.

The effect of the thermal mass is slightly lower when a single-zone model is used compared with the double-zone model. This is naturally due to

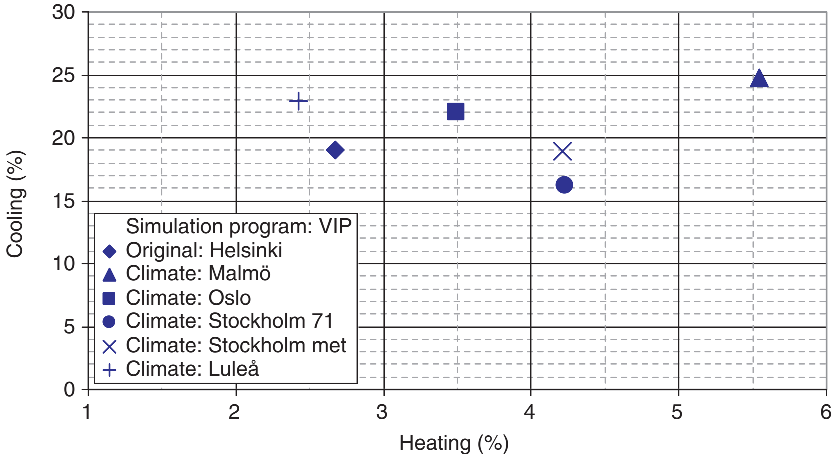

Figure 9. *Effects of weather data used and thermal mass on the relative difference between the needs for annual heating and cooling energy of the extra-light and the massive single-family houses. Single-zone building. Calculations made by VIP.*

perfect heat transfer inside the single-zone building which equalizes the differences in heating and cooling needs compared with those of the two-zone building.

When the massive and the extra-light single-family houses are compared with each other and when five Nordic weather data (Malmö, Stockholm (two different weather data), Luleå, Helsinki, and Oslo) are used in calculations made by VIP, the effect of thermal mass on cooling energy is ~20%. However, in South-Sweden (Malmö) the effect of thermal mass on heating energy is clearly higher than that in North-Sweden (Luleå) (Figure 9). The corresponding absolute energy consumptions for heating and cooling are from those of Malmö 35 and 35 kWh/m^2 to those of Luleå 75 and 25 kWh/m^2, respectively.

There is a need for cooling energy in well-insulated modern buildings also in Nordic climate. One way to decrease the need for mechanical cooling is to use night ventilation. The efficiency of night ventilation is better in a massive building than in a light building. Massive structures have a great thermal capacity for storing cooling energy from the night-time to the following day (Figure 10). With a triple-fold night ventilation air change rate compared with the corresponding basic ventilation rate (Table 5) the need for cooling energy can be decreased in the light apartment flat from 20 to 10 kWh/m^2 and in the massive house from 20 to 6 kWh/m^2 (calculation made by VIP), correspondingly.

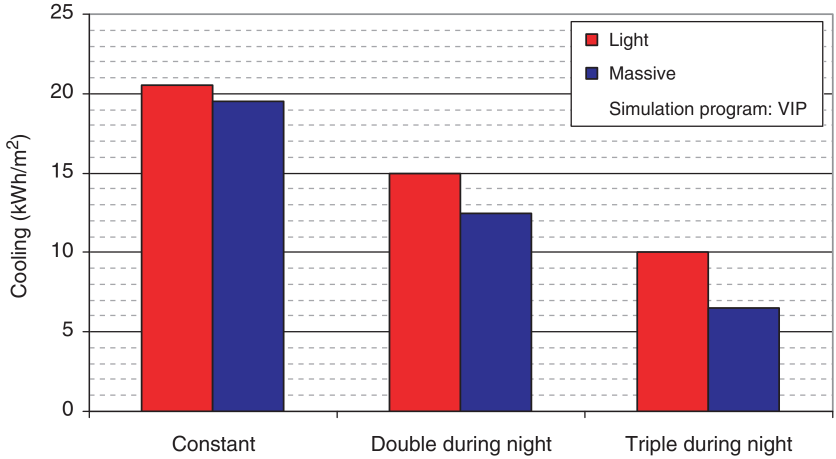

Figure 10. *Effect of night-ventilation and thermal mass on the annual cooling energy. Apartment flat. Calculations made by VIP.*

Effect of Windows' Size and Orientation

The basic orientation of the single-family house is such that the main facades are in east – west direction and the main windows are facing towards south. The basic value for window area/floor area is 12% (W 12%). The increase of windows' size from 12% to 45% from the floor area decreases the average thermal insulation level of the exterior envelope and at the same increases solar radiation into the building, especially during the spring and summer time. Therefore, due to this change the absolute heating energy increases by about 20 k Wh/m^2 and the cooling energy by 40 k Wh/m^2 (Figure 7). Thus from the point of rational energy use a too great window size is not reasonable.

However, if the windows' size is high and the main window area is facing towards south thermal mass can reduce heating energy need up to 10–15% and cooling energy need 30–40%.

Gain Utilization Factor

The gain utilization factor (Equation 14) is calculated for the single-zone, single-family house and for the two-zone apartment flat. For the latter heat loss (Q_{L1}) and net heating energy (Q_{NH2}) include the corresponding values of the two rooms of Figure 2. Three programs of this study (TASE, Consolis Energy and VIP) give very similar results for the gain utilization factor

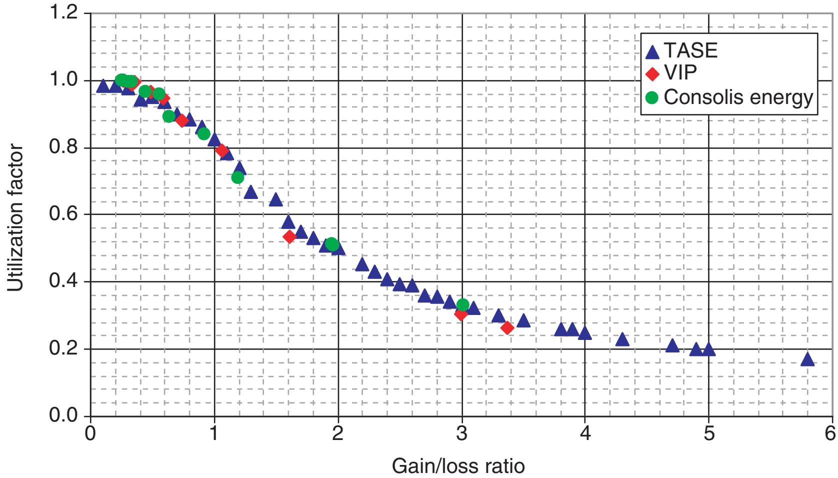

Figure 11. *Monthly gain utilization factor for the extra-light single-zone, single-family house according to TASE, VIP and Consolis Energy.*

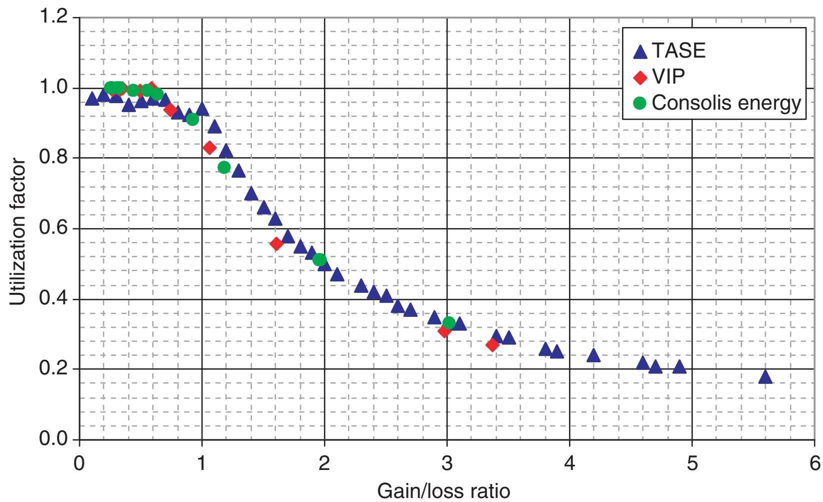

Figure 12. *Monthly gain utilization factor for the massive single-zone, single-family house according to TASE, VIP and Consolis Energy.*

of the extra-light and the massive single-family houses calculated as a single zone (Figures 11 and 12). Each point of these figures presents one monthly result calculated from Equation 14. The gain utilization factor of ISO DIS 13790 (Equations 3 and 4) with its parameters $a_0 = 1.0$ and $\tau_0 = 15\,\mathrm{h}$ gives

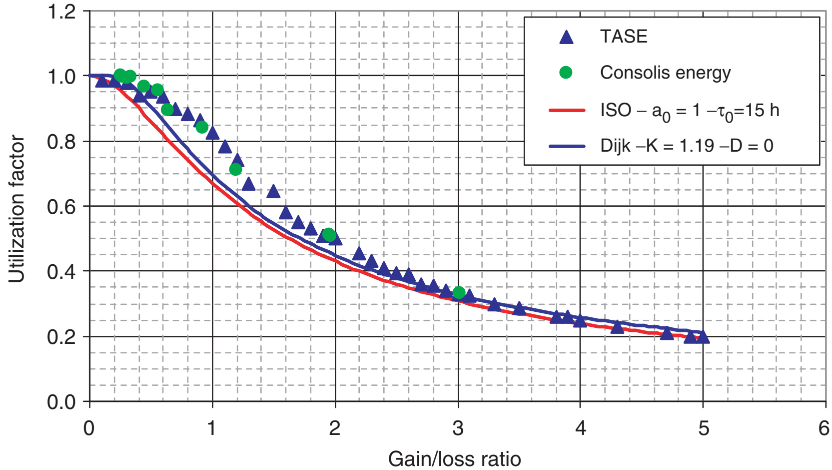

Figure 13. *Monthly gain utilization factor for the extra-light single-zone, single-family house according to TASE, Consolis Energy, ISO DIS 13790 and van Dijk and Arkesteijn.*

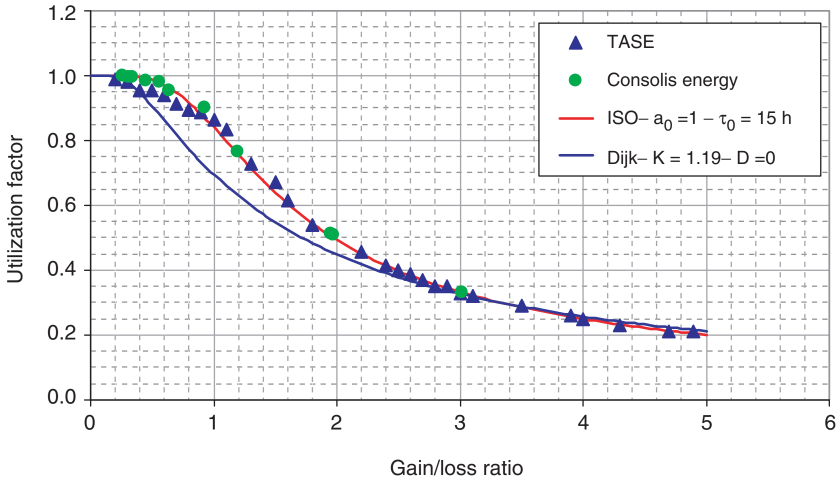

Figure 14. *Monthly gain utilization factor for the light single-zone, single-family house according to TASE, Consolis Energy, ISO DIS 13790 and van Dijk and Arkesteijn.*

accurate results for the light and for the massive single-family houses, but a too low utilization factor for the extra-light single-family house (Figures 13–15). The utilization factor of van Dijk and Arkesteijn (Equation 13) with its parameters for wooden and masonry type buildings (Table 2) give a clearly poorer fit for the utilization factor. One conclusion from

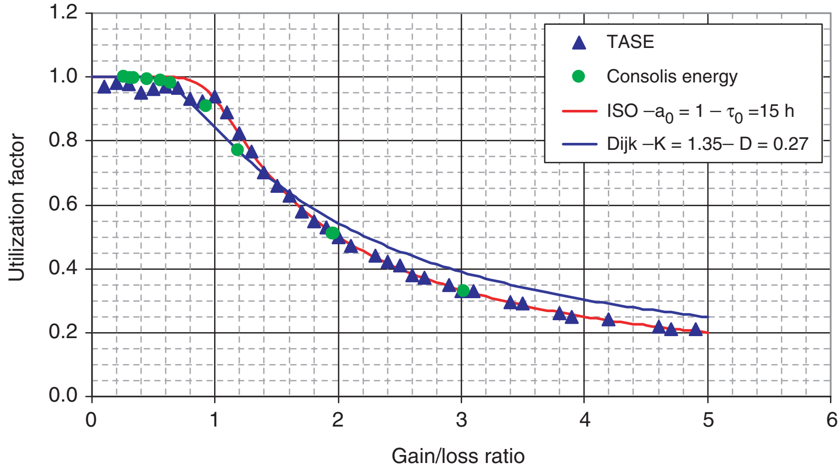

Figure 15. *Monthly gain utilization factor for the massive single-zone, single-family house according to TASE, Consolis Energy, ISO DIS 13790 and van Dijk and Arkesteijn.*

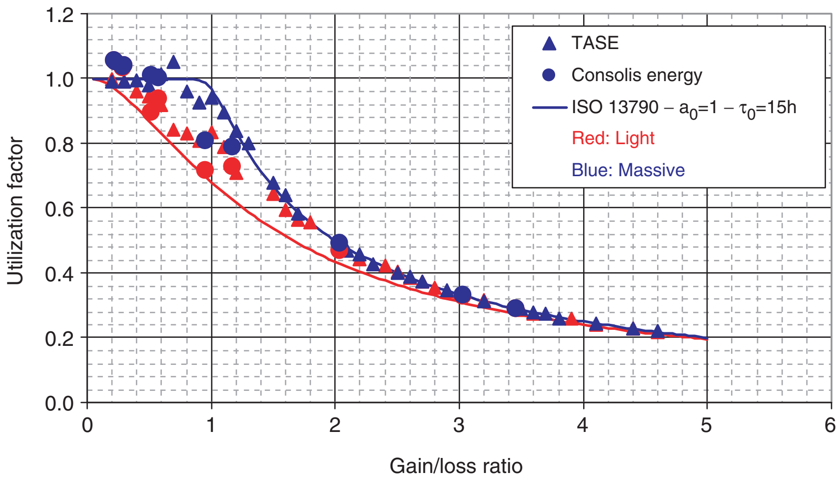

Figure 16. *Monthly gain utilization factor for the extra-light and for the massive double-zone apartment flat according to TASE, Consolis Energy and ISO DIS 13790.*

Figures 13–15 is that the utilization factor of ISO DIS 13 790 and its parameters are valid for Nordic climate for buildings, in which there is at least one massive surface (e.g., floor) and whose time-constant is at least 50 h.

The same conclusions, which can be drawn for the single-family house, can also be drawn for the apartment flat. For the extra-light apartment flat (time-constant ~20 h) the utilization factor of ISO DIS 13 790 is clearly too low compared with the utilization factors obtained with TASE and Consolis Energy (Figure 16). For the massive flat (time constant 410 h) the utilization factor of ISO DIS 13 790 fits on the average well with the simulation results.

However, the spread of the calculated monthly utilization factors for the apartment flat clearly is higher than that for the single-family house. One reason for this is that utilization factors for the single-family house were calculated using a single-zone model and those for the apartment flat a double-zone model.

CONCLUSIONS

This study had two main goals. The first purpose was to make a comprehensive study on the effects of thermal mass on heating and cooling energy in Nordic climate for modern, well-insulated Nordic buildings. Because various persons using different calculation methods get for the same research problem different results, seven researchers used six simulation programs (Consolis Energy, IDA-ICE, SciaQPro, TASE, VIP, VTT House model) and one monthly calculation method, maxit energy, in order to get reliable results on the effects of thermal mass. Maxit energy is based on the standard *EN 832 Thermal performance of buildings – Calculation of energy use for heating – Residential buildings,* which is the predecessor of *ISO DIS 13790*.

The second purpose was to evaluate the reliability of the calculation method of *ISO DIS 13 790* and especially its gain utilization factor in calculating the heating energy. In addition to these main goals some sensitivity analysis concerning e.g., the effects of the size of windows and the weather data on energy consumption were made.

The annual heating energy/floor-area is approximately from 60 to 70 k Wh/m^2 and the annual cooling energy from 3 to 13 k Wh/m^2 for the basic cases of the extra-light and of the massive single-family houses, calculated by the seven programs mentioned above. However, if the exact same cases are compared (same thermal mass and same number of zones) the maximum deviation of calculation results between various programs is both in heating and in cooling energy approximately 5 k Wh/m^2, when the results obtained with maxit energy and VTT House model are excluded. These two programs gave results which were not fully comparable with the results of other programs, maxit energy due to an error in the utilization factor of the extra-light building and VTT House model due to the detailed zoning with closed interior doors.

The basic value for the window area/floor area is 12% in the single-family house. When the window size is noticeably higher (45% from the floor area) and mainly south-facing, the annual heating energy is approximately $90\,\mathrm{k\,Wh/m^2}$ and that of cooling energy $\sim 60\,\mathrm{k\,Wh/m^2}$. The increase of the windows' size decreases the average level of thermal insulation of the envelope and increases solar radiation into spaces especially during spring and summer. This increases both heating and cooling energy needs.

The annual heating and cooling energy needs for the apartment flat show a spread from about 55 to $70\,\mathrm{k\,Wh/m^2}$ and from 20 to $50\,\mathrm{k\,Wh/m^2}$ for the light and the massive constructions and for the single-zone and double-zone cases, respectively, calculated by four programs (TASE, SciaQPro, VIP, and Consolis Energy). The main difference between the results of the single-family house and those of the apartment flat is that in the latter the need for cooling energy is noticeable higher. When the exactly same cases are compared the uncertainty in the calculation of heating energy is $\sim 5\,\mathrm{k\,Wh/m^2}$ and in that of cooling energy $20\,\mathrm{k\,Wh/m^2}$.

The uncertainly included in the calculation results, even when the input data is extremely detailed described, must be kept in mind, if e.g., national energy performance criteria is set as a $\mathrm{k\,Wh/m^2}$-value and the calculation method is left open. Especially the results for cooling energy can show a wide spread when calculated by different programs.

For the basic windows' area (12% from the floor area) the effect of thermal mass is $\sim 4\%$ ($3\,\mathrm{k\,Wh/m^2}$) in heating energy and 30–50% ($4\,\mathrm{k\,Wh/m^2}$) in cooling energy, when the extra-light and the massive single-family houses are compared. When the light single-family house having a concrete floor is compared with the massive one, the effect of thermal mass in heating energy is clearly smaller, a few percent. On the other hand, when the window size is greater (from 20 to 45% from the floor area) the differences in heating and cooling energy between the extra-light and the massive buildings can rise up to $15\,\mathrm{k\,Wh/m^2}$ (15%).

In the double-zone apartment flat the maximum differences in heating energy between the extra-light and the massive constructions are approximately the same as in the single-family house ($4\,\mathrm{k\,Wh/m^2}$), but those in cooling energy higher, ~ 5–$8\,\mathrm{k\,Wh/m^2}$. The three programs (TASE, Consolis Energy, and SciaQPro) give very similar results for the effect of thermal mass both for the single-family house as well as for the apartment flat.

The basic parameters of ISO DIS 13790 for the utilization factor ($a_0 = 1.0$ and $\tau_0 = 15\,\mathrm{h}$) give generally a good fit compared with the utilization factors calculated with the simulation models of this study. The fit is good with the exception, that these parameters give a too low utilisation factor for the extra-light buildings having no massive surfaces at all and a time-constant $<20\,\mathrm{h}$. Because so light buildings are very rare in practice, it can be concluded that the basic parameters of ISO DIS 13 790 are well-suited also for the Nordic climate and for modern Nordic buildings.

The gain utilization factor is the key parameter when calculating the monthly energy need using an energy balance method. The correctness of the utilization factor means that ISO DIS 13790 is an accurate calculation method for heating energy and its results are comparable in accuracy with the results of the simulation programs of this study. It can also be concluded that the utilization factor of ISO DIS 13 790 clearly gives more accurate results than that of van Dijk and Arkesteijn.

On the basis of this research we want to present the following conclusions:

1. Standard ISO DIS 13790 gives an accurate basis for calculating the annual heating energy, e.g., in the context of energy design and energy certification. Many times the inaccuracies of the input data and the various ways to interpret physical parameters cause greater effects on results than the simplifications in a calculation method.
2. The basic parameters of the utilization factor of ISO DIS 13790 ($a_0 = 1.0$ and $\tau_0 = 15$ h) are correct, when there is at least one massive surface in the building. For an extremely light building having no massive walls (time constant <20 h), the above mentioned coefficients give a too low gain utilization factor and thus a too high heating energy need.
3. Thermal mass of buildings has positive effects. It decreases noticeably the need for cooling energy and also slightly that for heating energy in well-insulated Nordic buildings. Especially, benefits from thermal mass can be achieved when the window size is great. Thermal mass can be effectively utilized together with night ventilation to reduce the need for mechanical cooling.
4. The inaccuracy in the calculation of heating energy is 5–8 k Wh/m^2 and in that of cooling energy 5–20 k Wh/m^2 for the single-family house and for the apartment flat, when the input data of calculations is exactly specified. If the energy consumptions were calculated so, that each calculator draws his/her input data directly from design documents the differences would be higher. One conclusion from these numbers is that authorities should be careful when setting energy performance requirements only on the basis of the calculated energy consumption. If a calculated specific energy consumption is wanted to fix to a certain level, then also the calculation method and the important input data must be fixed, in order to ascertain, that the calculated energy consumption also corresponds to a certain level of thermal insulation and efficiency of equipment.
5. For energy analysis purposes single-zone modeling seems to give results accurate enough compared with the double-zone modeling.

NOMENCLATURE

a = Parameter for taking into account the time constant (-)
C_{m} = Internal heat capacity (J/K)
H_{L} = Heat loss coefficient (W/K)
Q_{G} = Monthly heat gain (kWh)
Q_{i} = Monthly internal heat sources (kWh)
Q_{L} = Monthly heat loss (kWh)
Q_{NC} = Monthly net cooling energy (kWh)
Q_{NH} = Monthly net heating energy (kWh)
Q_{S} = Monthly solar heat sources (kWh)
Q_{T} = Monthly transmission heat loss (kWh)
Q_{V} = Monthly ventilation heat loss (kWh)
γ_{GH} = Gain/loss ratio for heating (-)
η_{GH} = Gain utilization factor for heating (-)
λ_{LC} = Loss/gain ratio for cooling (-)
η_{LC} = Loss utilization factor for cooling (-)
τ = Time constant (h)

Subscripts

C = Cooling
H = Heating

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