Comparison of Steady-State and Dynamic Building Energy Simulation Programs

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ABSTRACT

This paper presents the results of a comparison between EPW (Energie Prestatie Wetgeving, i.e., the new calculation method of the Flemish Energy Performance Regulation) and two transient building energy simulation programs: TRNSYS and ESP-r. The Energy Performance Regulation and the three calculation programs are described and their calculated net energy demands are compared to each other and to experimental data from a co-heating test. Considering the steady-state nature of the EPW model, the results of this research are very promising.

INTRODUCTION

In the Green Paper "Towards a European Strategy for Energy Supply" presented by the European Commission in 2000 (COM 2000), three main energy problems in Europe are highlighted:

- The dependency of the European Union on external energy sources.

- The increase of greenhouse gas emissions in the European Union, which makes it difficult to respond to the challenge of climate change and to meet the Kyoto Protocol.

- The limited scope of the European Union to influence energy supply conditions. It is essentially on the demand side that the EU can intervene.

These observations provide strong reasons to economize the use of energy wherever possible. The residential and tertiary sectors have been shown to be the largest overall end users with more than 40% of the total final energy consumed in the EU in 1997. This energy is mainly used for heating, lighting, appliances, and equipment. Numerous studies and practical experience show that there is a large potential for energy savings in this sector, probably larger than in any other sector (EU 2001).

The basic objective of Directive 2002/91/EC, the Energy Performance Regulation (EPR), is to promote the improvement of the energy performance of buildings within the EU and to ensure that only the most cost-effective measures are undertaken (EU 2003).

Given the low turnover rate of buildings (lifetime of 50 to more than 100 years) it is clear that the largest potential for improving energy performance in the short and medium term is in the existing building stock. The Directive lays down a framework that will lead to increased coordination between member states for legislation in this field. The requirements concern the following:

- The general framework for a common methodology of calculation of the integrated energy performance of buildings.
- The application of minimum requirements for the energy performance of new buildings.
- The application of minimum requirements for the energy performance of large existing buildings that are subject to major renovation.
- Energy certification of buildings.
- Regular inspection of boilers and of air-conditioning

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systems in buildings, in addition to assessments of heating installations in which the boilers are more than 15 years old.

Investments in energy efficiency can be made more attractive to building owners when they are able to provide clear and reliable information on the energy performance of buildings to prospective tenants or buyers. To facilitate the transfer of this information, energy certificates for new and existing buildings should be available when these are constructed, sold, or leased.

The Directive is based on an integrated approach in building standards and codes being developed both within and outside the EU (countries such as the U.S., Australia, Canada, and New Zealand). Nevertheless, the practical application of the framework will primarily remain the responsibility of individual member states. The laws, regulations, and administrative provisions necessary to comply with this Directive must be brought into force no later than January 4, 2006.

The Flemish Parliament voted its EPR, 'de Energie Prestatie Wetgeving' (EPW), on May 7, 2004. The methodology for residential buildings is listed in the second annex of this decree (VG 2003). This calculation procedure to determine the level of primary energy consumption in dwellings and residential buildings (E-level) is primarily based on the EN ISO 13790 (CEN 2004) and other European and Belgian codes. The yearly net energy demand is calculated by a steady-state approach with a constant indoor temperature and a mean monthly outdoor climate. The monthly energy consumption is determined by dividing the monthly net energy demands by the system efficiency and the heat production efficiency. In this manner, it is difficult to simulate the summer comfort or the transient behavior of the installation and its control. Is this calculation method accurate enough to be used in the EPW, the most important tool to reduce energy consumption in the residential and tertiary sector?

The Laboratory of Building Physics (LBF) of K.U. Leuven has developed a simulation tool in Visual Basic to do the calculations of the EPW for residential buildings. This paper will compare the net energy demand calculated by EPW with two widely known and used dynamic building energy simulation programs (BSPs): TRNSYS and ESP-r. The evolution of the BSPs will be briefly outlined, following which the performance of these programs will be analyzed by comparing the simulated net energy demand with each other and with the data from a co-heating test in the modeled building. Finally, conclusions will be stated and some persistent problems discussed.

BUILDING SIMULATION PROGRAMS

History

Until the mid 1960s only simple hand-calculation methods were available for estimating energy use in buildings. The degree-day method was commonly used to calculate heating energy requirements. The more detailed bin method was used for both heating and cooling analyses (Beausoleil-Morrison 2000). Although these methods were useful when computational resources were limited and expensive, they simplified and neglected some important factors such as transient thermal storage in building materials, solar gains, internal gains, variations in outdoor air ventilation and infiltration rates, and nonsteady operation of heating equipment.

The first simulation methods that treated time as the independent variable appeared in the mid 1960s. A typical modeling strategy was to divide the simulation in three sequential steps. In the first step, the building load was calculated using approximate techniques. Second, the loads were used as an input for the HVAC system, and finally, the outcome of the second stage was used to design the energy conversion machines. Because of this sequential nature, the interaction between the building and the system was ignored. EPW can be placed in this family of programs.

The first simplified building load models used time-averaging techniques, which smeared internal heat gains over a period of time to roughly approximate the transient thermal storage, radiation, and convection processes that were actually occurring. The response factor method of Stephenson and Mitalas (1967) significantly improved the capability of the models to predict transient effects. This room-air weighting method disconnected solar radiation from heat transfer through the envelope by using algebraic summation and weighting factors.

In the 1970s, heat balance methods replaced the room-air weighting factors. These methods were able to include most heat exchange phenomena in a physically correct manner. Although z-transfer functions were still common to calculate wall heat transfer, such as the method of Stephenson and Mitalas (1971) used in TRNSYS, the approach allowed some significant assumptions of linearity to be dropped.

Numerical discretization and simultaneous solution techniques were finally developed as a higher-resolution alternative to the response factor methods. The Ph.D. thesis of Clarke (1977) presented a first prototype of ESP-r. Essentially, this approach extends the concept of the heat balance methodology to all relevant building and plant components. A finite-volume (or finite-difference) discretization approach to the conservation of energy is employed to represent the opaque and transparent fabric, internal air spaces, and plant components.

EPW

EPW is a Visual Basic program based on the Flemish version of the EPR. The building is separated in "heating zones," i.e., parts of the building heated by the same installation. The air temperature in the zones is fixed at 18°C. Initially this temperature seems low, but as it is a mean temperature of the entire building, it is lowered by cooler temperatures in nonheated bedrooms, hallway, etc. Additionally, day/night schedules are also taken into account. The outside climate is

the monthly averaged Test Reference Year (TRY) of Ukkel (VG 2003).

The steady-state conduction losses are calculated one-dimensionally. Shortwave radiation gains should compensate for longwave radiation losses on the outside surfaces of opaque envelope elements. Inside, the total surface transfer coefficient is used to model the conductive, convective, and radiative heat transfer between the walls and the zone temperature. Outside dimensions are taken to account for geometric thermal bridges. Other thermal bridges are calculated with the EN ISO 10211 code (CEN 1995). For the heat transfer to the ground, the EN ISO 13370 code (CEN 1998) is used.

Ventilation and infiltration losses are also straightforward; the airflow depends on the quality and type of ventilation system and the airtightness of the building. This flow has to ensure the normal required amount of fresh air following the ventilation code *NBN D50-001* (BIN 1991).

The internal gains are estimated by the volume of the building and the number of families living there, while sun gains depend on the surface and type of glazing, type of sun shading, geometric shadow, orientation, inclination, and the amount of monthly averaged sun intensity on the surface. The radiative and convective energy gains are directly entered into the zone. However, not all of the gains are accounted for in the monthly heat balance as the net energy demand is the difference between losses and "useful" gains. These useful gains are the product of the total gains and a utilization factor η, which depends on the time constant of the building τ and the ratio of gains and losses:
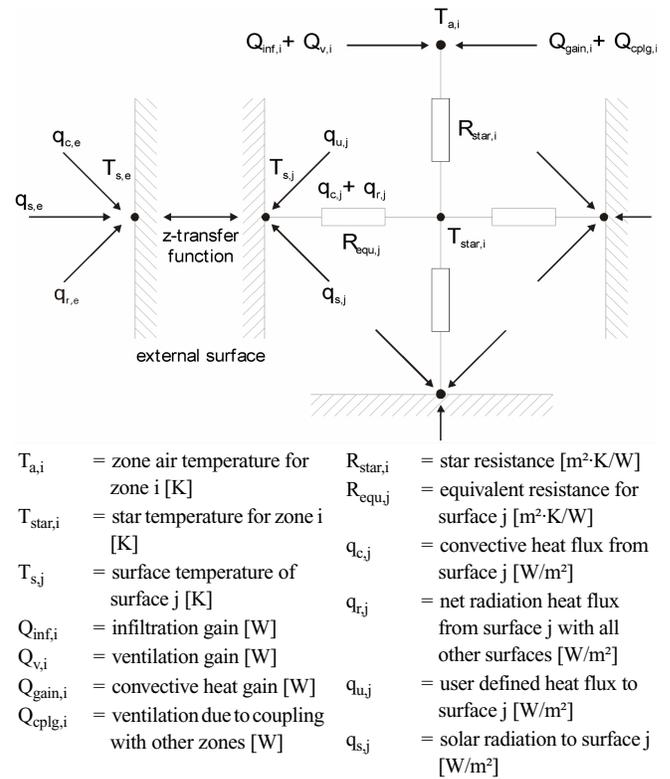
$$\eta_{useful, month} = \frac{1 - \left(\frac{Q_{gain, month}}{Q_{loss, month}}\right)^a}{1 - \left(\frac{Q_{gain, month}}{Q_{loss, month}}\right)^{a+1}} \text{, with } a = 1 + \frac{\tau}{57600}$$

and $\tau = \frac{C \cdot V}{H_{cond, month} + H_{vent, month}}$

The losses are calculated with an indoor temperature of 18°C and the time constant depends on the capacity of the building C (J/[m³·K]), the protected volume V (m³), and the specific conductive and ventilative heat losses H_{cond} and H_{vent} (W/K). In this way, transient thermal storage is approximated.

Summer comfort is checked by calculating the "gain surplus." Gain surplus is calculated by subtracting useful gains from the total gain, but at an indoor temperature of 21°C instead of the 18°C used in the heating season. The sum of all the gain surpluses over the year can be regarded as a cooling load. If this load is too high, overheating is likely to occur.

After monthly net energy demands are estimated, they are first converted into monthly energy uses, using system and production efficiencies, before being converted into yearly primary energy use. The E-level can then be calculated from the primary energy use and from the volume and the envelope area of the building. Since this paper focuses on the net energy

$T_{a,i}$	= zone air temperature for zone i [K]	$R_{star,i}$	= star resistance [m²·K/W]
$T_{star,i}$	= star temperature for zone i [K]	$R_{equ,j}$	= equivalent resistance for surface j [m²·K/W]
$T_{s,j}$	= surface temperature of surface j [K]	$q_{c,j}$	= convective heat flux from surface j [W/m²]
$Q_{inf,i}$	= infiltration gain [W]	$q_{r,j}$	= net radiation heat flux from surface j with all other surfaces [W/m²]
$Q_{v,i}$	= ventilation gain [W]		
$Q_{gain,i}$	= convective heat gain [W]	$q_{u,j}$	= user defined heat flux to surface j [W/m²]
$Q_{cplg,i}$	= ventilation due to coupling with other zones [W]	$q_{s,j}$	= solar radiation to surface j [W/m²]

Figure 1 *Star network approach in the TRNSYS TYPE 56 building simulation component.*

demand, such conversions are beyond the scope of the present discussion.

TRNSYS

TRNSYS (SEL 2000) is a TRaNsient SYStem simulation program developed at the Solar Energy Lab of the University of Wisconsin-Madison and the Solar Energy Application Lab of the University of Colorado. It was originally developed for modeling active solar systems and became commercially available in 1975.

TRNSYS is designed to simulate the transient performance of thermal systems. The program has a modular approach to solve systems of components called types. Each type is described by a FORTRAN subroutine, which can be linked to represent the simulated system. The building models in TRNSYS range from a simple lumped-capacitance building model to detailed single- and multi-zone building models. In this paper TRNSYS version 15 and the multi-zone building model (TYPE 56) are used.

Figure 1 (Saelens 2002) shows a schematic representation of the most important heat fluxes in TYPE 56. At the exterior surface, the longwave radiation and the convective heat exchange are separated and the absorbed solar radiation is accounted for. The transient heat exchange that occurs through zone surfaces is calculated with the previously

mentioned z-transfer function method of Stephenson and Mitalas (1971). The longwave radiation exchange between the surfaces within a specific zone is approximated by the star network method implemented by Seem (1987). The interior surface temperatures are linked to a "star temperature" by equivalent resistances. The star temperature is, in turn, linked to the zone air temperature by means of a star resistance.

The main drawbacks of the TRNSYS program include:

- old-fashioned techniques that are used to model transient heat exchange in the building simulation component, such as the z-transfer function, which complicates the modeling of heavy structures such as a floor slab with soil,
- the simplification of the radiant heat exchange to a star temperature approach,
- the cumbersome input of the building data without any check on the surface areas and zone volumes.

On the other hand, TRNSYS has the advantages of

- being well documented and validated (Lomas et al. 1997; Blair and Holst 1998; Holst 1993),
- the availability of the source code,
- the modular structure, which allows users to include self-written code or to use one of many types developed by other researchers,
- the possibility of linking TRNSYS to other programs such as Matlab, Excel, Comis, and E+.

ESP-r

ESP-r stands for "Environmental System Performance-research" and was developed by the Energy Systems Research Unit of the University of Strathclyde (Citherlet 2001). The ESP-r building simulation system (ESRU 2002) has been in a constant state of evolution and renewal since its first prototype was developed over two decades ago (Clarke 1977). Version 10 is used in this paper. More resolved and advanced modeling approaches have been incorporated and the program now includes the simulation of non-energy domains.

ESP-r's project manager controls all aspects of model creation, simulation, and results analysis, while providing a graphical and interactive interface between the user and the underlying data model. It controls the maintenance of databases, the execution of pre-simulation calculations (e.g., to predict solar insolation and shading, to determine radiation view factors), the performance of the time-step simulation of heat, air, moisture, and electric power flow, and the visualization of results.

ESP-r uses a partitioned solution approach, applying customized solvers to each model domain (thermal, electric power flow, interzonal airflow, intrazonal airflow, etc.). This enables an optimized treatment of each of the different equation sets. In this manner, one solver processes the thermal domain while another treats network airflow (to resolve inter-
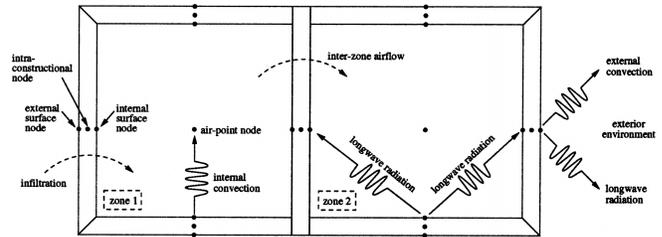
Figure 2 *Finite-difference discretization and inter-nodal heat flows used by ESP-r.*

zonal flow) and yet another handles CFD (for predicting intra-zonal airflow).

ESP-r's thermal simulation methodology is based on the numerical discretization and simultaneous solution of heat-balance methods. Specifically, ESP-r calculates the thermal state of the building by applying a finite-difference formulation based on a control-volume heat balance to represent all relevant energy flows. There are three principal steps:

1. The building is discretized by representing air volumes (such as rooms), opaque and transparent fabric components (walls, windows, roofs, floors), solid-fluid interfaces (such as the internal and external surfaces of walls and windows), and plant components (such as boilers and heat exchangers) with finite-difference nodes. Numerous nodes are placed through each component to represent these multi-layered constructions. A small number of such nodes is illustrated in Figure 2 (Beausoleil-Morrison 2000).

2. A heat balance that incorporates the relevant energy flow paths (some are shown in Figure 2) is written for each node. These balances are put in algebraic and discrete form and thus approximate the partial differential equations that rule the heat transfer. As each heat balance expresses the thermal interaction between a node and its neighbors, the resulting equations link all internode heat flows over time and space.

3. A simultaneous solution is performed on the equation set to predict the thermal state of each node and the heat flows between nodes, for a given point in time.

Steps 2 and 3 are repeated to reform and resolve the equation set for each subsequent time-step of the simulation.

The ESP-r program includes additional capabilities for solving a wide range of problems; it is able to perform indoor CFD calculations, light intensity calculations, life-cycle cost analysis, and input via CAD, etc. It is free for research purposes and has an open source GNU-LINUX philosophy.

STUDY OBJECT

The building that has been modeled to make the current comparison is a low-energy building from a social housing company. During the past four years, several parameters of the

Table 1. Mean Characteristics of the Studied Building

	Area		Averaged U-Factor		G-Value (SHGC)
	m²	ft²	W/(m²K)	Btu/(h·ft²°F)	[-]
Floor: slab on ground	58.7	631.9	0.33	0.06	
Walls	85.1	961.0	0.25	0.04	
Roof	84.2	906.4	0.16	0.03	
Door	2.2	23.7	2.52	0.44	
Windows (with frame)	21.0	226.0	1.6	0.28	0.504

	A_T		V		Compactness = V/A_T	
	m²	ft²	m³	ft³	m	ft
Total	251.3	2705	354.4	12514	1.4	4.6

Table 2. Heating Demands and Conduction Losses with Sun, Without Solar Transmission through Windows and Without Solar Energy

	Sun	Shading	Eclipse
	MJ/y	MJ/y	MJ/y
Qheating	568290	585457	588399
Qventilation	-555120	-555120	-555120
Qconduction	-46860	-44661	-47603
Δ Qheating	Ref	17168	20110
Δ Qconduction	Ref	2199	-743
Sum		19366	19366

semi-attached house have been measured (Hens 2000; Hens 2001):

- Infiltration by a blower door test $\Rightarrow n_{50} = 3$ ACH $\Rightarrow n_{inf} = 0.1$ ACH outside air
- Performance of the ventilation system $\Rightarrow n_{vent} \approx 0.45$ ACH outside air
- Net energy demand by a co-heating test (without inhabitants and ventilation losses, see also below) $\Rightarrow Q_{net} \approx 100$ MJ/day (94772 Btu/day)
- Insulation quality by a heat flow measurement and IR-photographs $\Rightarrow$ check on given insulation data

Table 1 summarizes the mean characteristics of the building.

The availability of these data makes it a suitable building to compare the BSPs; however, this is not a validation, as one of the criteria for an acceptable data set is not met (Lomas et al. 1997)—the weather data are not collected at the site of the building but at the VLIET test building 30 km away. Furthermore, the internal gains and inhabitant behavior are unknown. For these inputs, the standard values of EPW are used, i.e., a constant internal temperature of 18°C and a constant internal gain depending on the volume of the building, in this case, 457 W.

INTERMODEL COMPARISON

Harmonization of Output Definitions

Since the results of the different BSPs are compared, we must first make sure that these results have the same physical meaning. Net energy demand is easy to define, as in EPW it is given explicitly and in TRNSYS and ESP-r it can be modeled as the energy consumption by choosing an ideal installation with perfect control and unlimited power. If we want to scrutinize the results, however, and compare the different gains and losses, the definitions become less evident.

Solar Gains vs. Conduction Losses. The solar gains calculated with TRNSYS are higher than those calculated with ESP-r and EPW. The conduction losses are also higher. These differences are due to variations in definition that become more evident if we consider three situations where solar gains are the only variable.

In this exercise the indoor temperature is a constant 18°C, and there is no need for cooling as the outdoor temperature is lowered and infiltration rate is increased. There are no internal gains, and heat transmission from an ideal heater is 100% convective. The first case where the solar gains can enter freely without sun shading is the reference. The "shading" case reflects all solar radiation that would pass through the windows and only considers solar energy absorbed in the opaque wall. The "eclipse" case does not have any insolation. Table 2 gives the energy demand and conduction losses for these three cases.

If the solar energy through the windows is blocked, the heating demand increases but the conduction losses drop. This is due to the lack of shortwave radiation that would normally heat up the inside of the envelope, while the outside is still radiated by the sun.

If there is no more solar energy, the heating demand increases further and the conduction losses rise. The opaque walls do not absorb any solar energy and the outside surface temperature drops. This causes higher conductive losses. Including solar absorption of opaque walls in the solar gain will result in higher solar gain. However, as the solar absorption cannot be included twice, it will not take part in the conduction and this results in higher conductive losses.
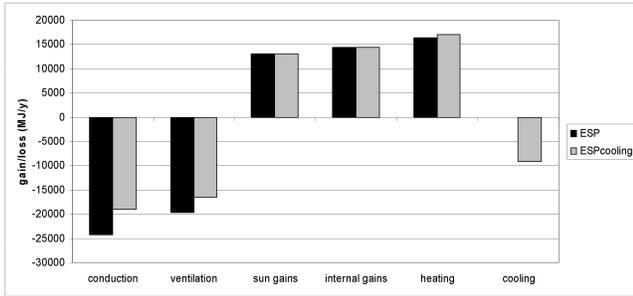
Figure 3　*The influence of cooling on the yearly heat flows calculated by ESP-r: a strong decrease of conduction and ventilation losses in summer.*

Figure 4　*The influence of the definition of gains on the yearly heat flow calculated by EPW: counting in all the gains instead of only the useful gains causes a rise in temperature which is countered by cooling and higher conduction and ventilation losses.*

Results given in a BSP are highly dependable on the definition of solar gain and conduction loss. Nevertheless, this topic is not considered in the manual of the three simulation programs. To be consistent with the definition of solar gains in EPW, the only solar gains that should be accounted for are those that enter the zone through the transparent elements.

Gain Surplus vs. Cooling. To asses summer comfort EPW uses the "gain surplus." It is a measure of gains offered to the building when indoor temperature is above 21°C. This parameter does not exist in simulations with transient ESP-r and TRNSYS. Introducing cooling that limits the temperature to 21°C will produce a comparable effect. This cuts back ventilation and conduction losses due to drastic decreases in indoor temperature during summer. The influence of cooling on ventilation and conduction losses is shown in Figure 3.

Useful vs. Total Solar and Internal Gains. As mentioned previously, EPW considers whether gains remain useful and only these "useful" gains, which raise the indoor temperature up to 18°C, are entered into the zone energy balance. Consequently, the losses are calculated using the maximum temperature of 18°C. In the case of the transient BSPs, the indoor temperature is not fixed and the gains are always offered to the zone. This leads to an increase in indoor temperature when there are more gains than losses.

If we also add useless gains into the energy balance of EPW and calculate using total gains, the increase in gains will be cooled above 21°C and the "surplus" will be redefined as "cooling." In comparison, rises of temperature between 18°C and 21°C will result in an increase in ventilation and conduc-tion losses (Figure 4).

Conclusion. Figure 5 shows the nonharmonized outputs. ESP-r and TRNSYS have lower net energy demand (heating) while the losses should be higher than EPW.

If the gains and the conduction losses do get the same defi-nition for the three BSPs and cooling is included in the model for ESP-r and TRNSYS to avoid surplus gains, the results can be accurately compared. Figure 6 shows that the difference in net energy demand between EPW and the others is mainly due to higher conduction losses. The conduction losses of ESP-r
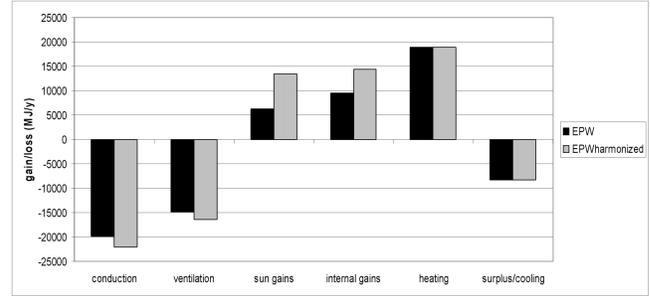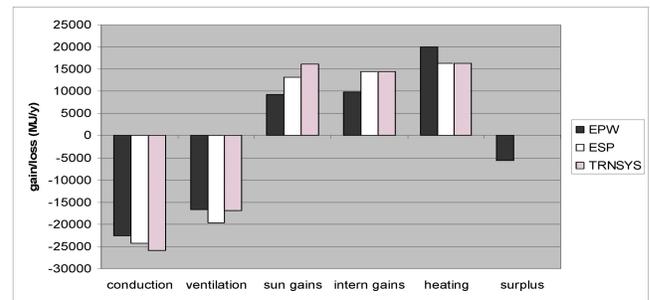
Figure 5　*The preliminary calculated net energy demand (heating) and the other heat flows of the three BSPs without harmonization of outputs.*
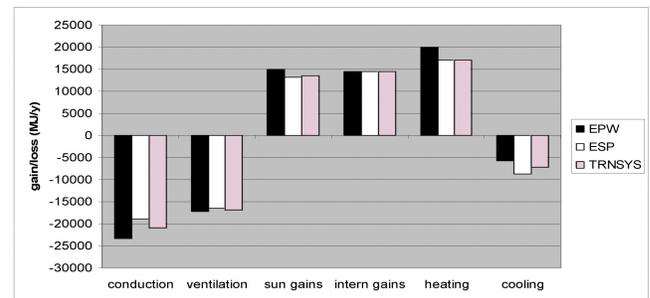

Figure 6　*The preliminary calculated net energy demand (heating) and the other heat flows of the three BSPS with harmonization of outputs.*

are at the low end. These differences will be scrutinized in the following section.

Harmonization of Inputs

Despite our efforts to provide identical input parameters, differences exist due to different modeling requirements of individual programs. This section will outline some of the more important differences that exist.
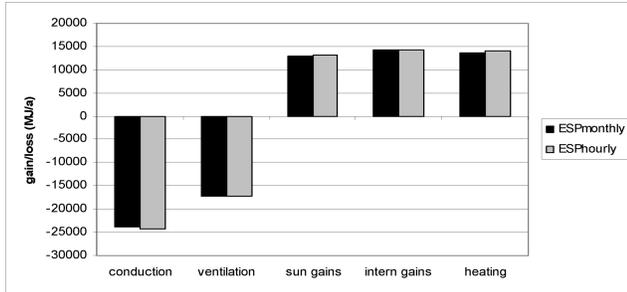
Figure 7   The heat flows calculated with ESP for the hourly and monthly climatic data.

Figure 8   The calculated net heating demand, net cooling demand and the other heat flows of the three BSPs (ESP with variable and fixed convection coefficients).

Climatic Data. The monthly averaged climatic data of the Test Reference Year (TRY) of Ukkel (Brussels) is hardwired in the basic version of EPW, while the other programs used the climatic data of the VLIET building of 2001, as this is the year of the co-heating test. The TRY of Ukkel is used in the three BSPs from this point on.

However, there is still a difference, as EPW requires the mean monthly values and the other two transient programs use hourly data. Nevertheless, this only has a minor influence on net heating demands as indicated by the comparison with ESP-r between mean monthly and hourly data (Figure 7). Heat demand using mean monthly values will be leveled out over the days; however, if integrated over the entire heating season, it will result in a comparative yearly heat demand, as the heating season is fairly succinct (ranging from November until April) and the indoor temperature is maintained at a constant 18°C by an ideal heating system.

In summer, however, the outdoor environment interacts with the indoor environment resulting in variations to indoor temperature. Without cooling, the maximum indoor temperature for the mean monthly data is calculated as 32°C, while temperatures calculated with hourly climatic data reach 38°C. When cooling is applied, the hourly data result in much higher cooling loads. To model the summer conditions correctly in ESP-r and TRNSYS, the hourly data are used for simulations in this paper.

Outside Dimensions. To take geometric thermal bridges into account, EPW and TRNSYS use outside dimensions as input. The dimensions of ESP-r are put in geometrically and, therefore, inside dimensions are necessary to calculate the correct zone volumes. Nevertheless, it uses one-dimensional heat transfer like the other programs. ESP-r has the ability to calculate the flows three-dimensionally, but this is no standard practice. The inside dimensions will lead to lower conduction losses and, therefore, a lower net energy demand. To make the comparison more correct, outside dimensions are used in the three simulation programs.

Convection Surface Film Coefficient. In ESP-r the convection surface film coefficients at the inside surfaces of
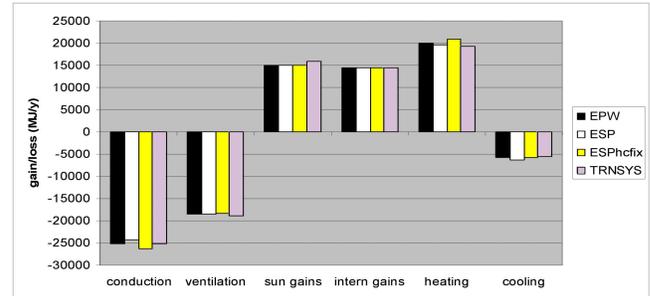
the zone envelope are recalculated for each time-step. By default, the Alamdari and Hammond (1983) correlations for buoyancy-driven flow are used. These equations express the convection coefficient as a function of the surface characteristic dimension and the surface to air temperature difference (Clarke 2001).

This contrasts with the treatment of EPW, which employs time-invariant convection coefficients. It has a fixed coefficient for the total heat transfer (including longwave radiation) to and from inside surfaces of 8.0 W/m^2·K (1.41 Btu/[h·ft²· °F]) for walls and ceilings and 6 W/m²·K for floors. TRNSYS has a user-defined coefficient for the convective surface film coefficient. This can either be a constant or depend on other variables, such as the surface to air temperature difference. A constant value of 3.0 W/m^2·K (0.53 Btu/[h·ft²·°F]) for the walls and ceilings is chosen for the calculations in this paper.

Another set of correlations for buoyancy-driven flow may also be employed in ESP-r, and these equations are extracted from an experimental study conducted in a room-sized test cell (Khalifa and Marshall 1990). It is interesting to note that this method produces substantially different convection coefficients. For example, using a wall 2.4 m high with 3°C surface-air temperature difference, the Alamdari and Hammond correlation gives a convection coefficient of 1.9 W/m^2·K (0.33 Btu/[h·ft²·°F]), whereas the Khalifa and Marshall equation calculates a value of 3.0 W/m^2·K (0.53 Btu/[h·ft²·°F]) (Beausoleil-Morrison 2000).

The user also has the option of employing time-invariant values rather than recalculating convection coefficients at each time step. The value of 3.0 W/m^2·K is added to observe the differences in conduction losses that are produced.

Final Results

If the inputs and outputs are harmonized, the results of the three BSPs are very close (Figure 8 and Table 3). EPW results in the highest net heating demand, while TRNSYS calculates the lowest. The difference between these two is less

Table 3.   Net Heating and Cooling Demands Calculated by the Three BSPs

	EPW		TRNSYS		ESP		ESPhcfix	
	MJ/y	kBtu/y	MJ/y	kBtu/y	MJ/y	kBtu/y	MJ/y	kBtu/y
$Q_{net,heat}$	19989	18931	19193	18177	19692	18650	20977	19867
$Q_{net,cool}$	5660	5360	5565	5270	6386	6048	5796	5489
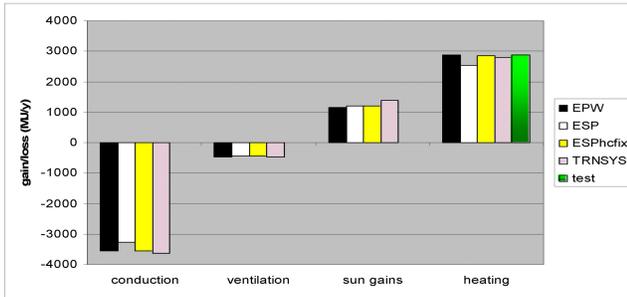
Figure 9   *Net energy demand calculated by the three BSPs (ESP with variable and fixed convection coefficients) and measured by a coheating test.*

than 4%. Fixing the convective transfer coefficients of ESP to 3.0 W/m²·K (0.53 Btu/[h·ft² ·°F]) for the indoor environment and 17.8 W/m²·K (3.13 Btu/[h·ft²·°F]) for the outdoor, causes higher conduction losses and thus increases the net heating demand and decreases the net cooling demand.

The cooling demand calculation of EPW is remarkably precise, keeping in mind that the outdoor climate is averaged monthly. The necessary power of the cooling plant cannot be determined and the transient effects cannot be researched with the steady-state method, but it performs well for calculating the yearly energy that must be removed from the building in order to prevent the temperature from rising above 21°C.

COHEATING TEST

After the first comparison between the calculated yearly energy demands, the results of the BSPs are compared with data from a co-heating test.

The net energy demand in the low-energy dwelling was measured over 29 days using electrical heaters coupled to a temperature control in the building. In this manner the indoor temperature was kept constant at 23.7°C and the energy used for heating was measured. The test building was inhabited during the test, and precautions were taken to ensure that other internal gains were measured at the same time. The ventilation shafts were taped off and the infiltration losses were estimated from the blower door test. The insulation quality was validated locally by using heat flow meters and IR photography. The outside temperature was logged at 10-second intervals. Solar intensity, wind, and temperature distribution were not measured on site. Consequently, these parameters may still lead to differences between measurement and calculation.

The coheating results were used to validate the BSPs and Figure 9 shows that measurements and calculations are comparable. Both EPW and TRNSYS results differ by less than 2% from the measured net energy demand. ESP-r underestimates heat loss by 10%; however, fixing the convection coefficient as a constant substantially improves results.

DISCUSSION

Both TRNSYS and ESP-r calculate a slightly lower net energy demand than EPW. The intermodel comparison of 18 BSPs by Lomas et al. (1997) shows differences of up to 40% in simulated energy demand. In the study of Lomas et al. the programming of the BSPs was undertaken by different users and as these results are highly sensitive to input parameters, the significant impact differing users have on results is indicated. Other interpretations of the input and/or the output data can cause large variations in the outcome, as shown in Figure 5.

It is interesting to note that all versions of ESP-r and TRNSYS used in the validation with experimental data of Lomas et al. underestimate the energy demand. For TRNSYS, versions 12 and 13.1 were included, and for ESP-r, version 7.7 was used. In this paper the evolved and improved TRNSYS version 15 and ESP-r version 10 are employed. The underestimation of longwave radiant losses that caused the problems in older versions of TRNSYS has been resolved by implementing an effective sky temperature. Furthermore, the window model is improved and convection and radiation decoupled in the ideal heating and cooling mode. The problems with ESP-r were mostly due to difficulties in choosing the right parameters, such as the aforementioned variable convection coefficient.

As Figures 8 and 9 indicate, solar gains may still be overestimated, which would cause underestimation of the net energy demand. In the same way, the longwave radiation losses to the environment can be overestimated by EPW. The longwave radiation losses are thought to compensate for the shortwave radiation gains on the opaque envelope elements. This greatly simplifies the calculations, as a separation between convection and radiation is not necessary for conductive losses or gains, although this approach deviates from reality.

Another reason for the difference in the outcomes of the intermodel comparison may be due to an underestimation of the "utilization factor" in EPW, i.e., the transient thermal stor-
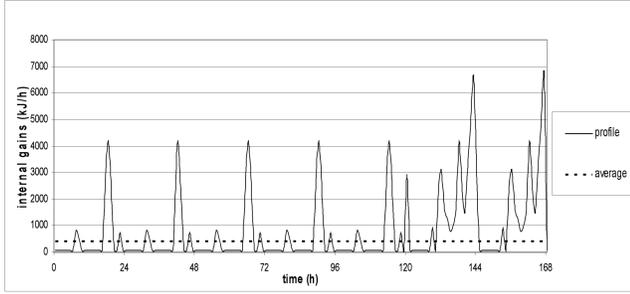
Figure 10 *Internal gain profiles used as input in calculations for the living room with TRNSYS: a typical profile and the time- and space-averaged internal gains as used by EPW.*

age. An increase in capacity from 24 MJ/K to 42 MJ/K leads to a higher time constant of the building and more used gains; the net energy demand lowers to 19310 MJ/y, i.e., a value between TRNSYS and ESP-r. However, caution should be taken as previously the only transient element in the inter-model comparison has been outdoor climate. If the internal gains are entered into TRNSYS with a profile such as that outlined in Figure 10, which simulates the internal gains of a typical family hour per hour and depending on the zone, this will be a second dynamic input.

If we compare the net energy demand of this case with the net energy demand for the same internal gains averaged over time and for the entire volume of the building, such as calculated previously, we get 19885 MJ/y rather than 19193 MJ/y. These dynamic gains cannot be used to the same extent as the mean gains.

It is not possible to model the internal gain profile correctly in EPW, since these gains must be at least averaged monthly. Also, the day/night regimes that cannot be modeled in EPW will have an impact on the net energy demand. The effect is probably reversed, since indoor temperature is higher during the day when internal gains are also higher.

The lack of modeling of this inhabitant-specific behavior does not have to be a problem, as the energy performance of buildings must be assessed independently of inhabitants. Prior knowledge regarding internal gains and temperature control regimes is unavailable. However, a good estimation of the "utilization factor" must take the average of these effects into account, as, if these effects are not considered, the profit from the gains may be overestimated and the net energy underestimated compared with reality in situ.

The problems with this transient behavior will come back when the total energy consumption is calculated. The actual system and production efficiencies will depend on transient effects. The efficiency data in EPW must take this into account. This will be the topic of our future research.

The last difference in the calculations of the energy demand is ground conduction. EPW uses the EN ISO 13370

for the calculation of ground heat transfer to and from buildings. For a slab-on-ground floor with a constant inside temperature, which is the case for EPW, the average rate of heat transfer with the ground in month m can be written as

$$\Phi_m = L_s(\bar{T}_i + \bar{T}_e) + L_{pe}\hat{T}_e\cos\left(2\pi\frac{m-\tau-\beta}{12}\right) \text{ (W)},$$

where L_s = steady-state thermal coupling coefficient,

$$L_S = AU_0 = A\frac{\lambda}{0.457\frac{2A}{P} + dt} \text{ (W/K)};$$

L_{pe} = external periodic thermal coupling coefficient,

$$L_{pe} = 0.37P\lambda\ln\left(\frac{\delta}{dt} + 1\right);$$

β = phase difference between the soil temperature and the air temperature,

β = $1.5 - 0.42\ln\left(\frac{\delta}{dt} + 1\right)$

$\bar{T}_i$ = annual average internal temperature (°C);

$\bar{T}_e$ = annual average external temperature (°C);

$\hat{T}_e$ = amplitude of variations in monthly mean temperature (°C);

τ = month number in which the minimum external temperature is reached;

A = surface of the floor (m²);

P = exposed perimeter of the floor (m);

λ = thermal conductivity of unfrozen ground (W/m K);

dt = $w + \lambda (Rsi+Rf+Rse)$ is the characteristic dimension for the floor (m);

w = thickness of the external walls surrounding the building (m);

Rf = resistance of the floor slab (m²K/W);

Rsi,e = internal and external contact resistance (m²K/W);

δ = $\sqrt{\frac{\lambda t_p}{\pi C}}$ periodic penetration depth (m);

t_p = one year expressed in seconds (s); and

C = capacity of the ground (J/K).

When all variables of the modeled building and surrounding climate are entered into the equation, it can be represented as seen in Figure 11.

ESP-r has a three-dimensional ground module to calculate the heat transferred to the ground. TRNSYS only allows for one-dimensional heat flow. Nevertheless, heat losses can still be modeled fairly correctly by putting an adiabatic boundary with fluctuating temperature in the surface under the floor slab. Temperature is determined in a way that heat flow, calculated with the U-factor of the floor, equals the value given by the EN ISO 13370 (CEN 1998).

Problems arise when indoor temperature is not constant. The upper part of the soil contributes to the capacity of the floor. The standard solution is to put the adiabatic boundary
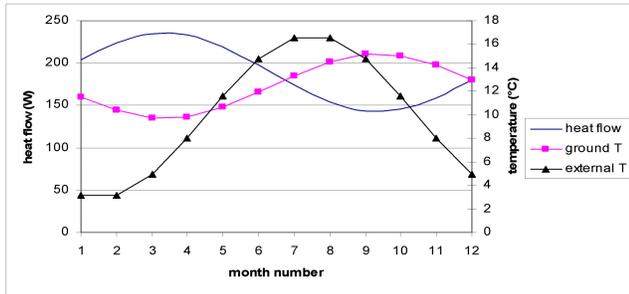
Figure 11 *External temperature, ground temperature, and heat flow through the ground slab of the modeled building (Rf = 2.8 m²K/W, Ti = 23.7°C, depth = 1 m).*

Figure 12 *Temperature of zone in free flow (dotted line) and difference in modeled heat flow out of the ground. The reference is a slab without extra capacity from the soil, the other has 0.4 m of soil.*

one meter below the floor slab. Soil below this depth hardly influences indoor climate. However, this is not possible with TRNSYS. In our case, using a 200 mm concrete floor with 80 mm XPS insulation, the maximum soil thickness that can be modeled is less than 0.4 meters. This is due to limitations of transfer functions that are used in the building module of TRNSYS.

The influence of this 0.4 m of soil becomes obvious when the building is allowed to cool down after being kept at a constant 23.7°C for an extended period. The temperature goes in free flow and a difference in heat flow through the ground slab is measured between the cases of soil with capacity and without capacity (Figure 12). During the first hours, there is no difference; the capacity of the soil begins intervening after five hours. A peak in heat flow of 170 kJ/h (161 Btu/h) is reached at 29 hours, and after 200 hours the difference returns to zero. The peak indoor temperature at approximately 120 hours is caused by solar gains, although these minor peaks do not influence soil interaction.

The soil does not interact with the building as long as the temperature changes over a few hours. It will not influence intermittent heating, but it will have an effect in the summer period; the extra capacity of the soil will cool the indoor air temperature during the first days of a hot week. Since these hot periods are critical for summer comfort in Belgium, the influence of the soil cannot be neglected.

The zone from 0.4 m to 1 m, or deeper, will intervene later in the heat flow. This is cannot be measured with the regular TRNSYS building model. However, a type with a three-dimensional finite difference model of the soil, which interacts with the surface temperature of the floor slab, has been developed by TESS and this type is bought to research this problem further.

CONCLUSIONS

The final results of the intermodel comparison show that the steady-state EPW program predicts a net energy demand
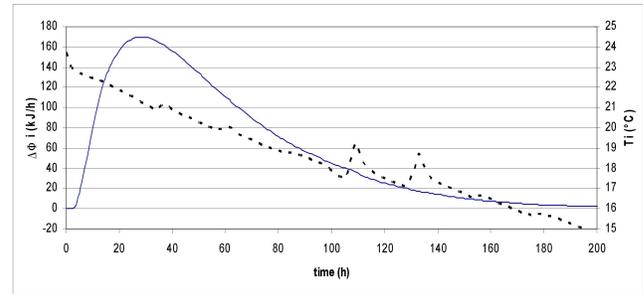
that is approximately 4% higher than the more advanced BSPs TRNSYS and ESP-r. This is acceptable as EPW takes the lower usage of transient internal gains into account, although it cannot be modeled. As long as the correct average indoor temperature is used in modeling, EPW performs well. The capacitive effects of the building will not influence the net energy demand when a longer period is assessed.

The calculated net cooling demand is also comparable to the outcomes of ESP-r and TRNSYS, remarkably precise for a calculation method based on mean monthly values.

When comparing the programs with empirical data from the co-heating test in which the indoor temperature is kept constant, internal gains are put to zero, and the efficiency of the system is 100%, results are outstanding.

Intermodel comparison revealed that it is necessary that the individual using the BSP have a good comprehension of the physical meaning for all inputs and outputs of the program. Comprehensive, well-written manuals are therefore necessary, and training programs would greatly accelerate the learning process.

The well-known and steep learning curve of programs such as TRNSYS and ESP-r could cause problems if these programs were used within the framework of the EPR. The many default values and rules of thumb in EPW are an advantage in this context, especially in the Belgian residential sector, which is characterized by a large number of single-family housing. These are usually unique projects with the entire design process undertaken by one architect (WTCB 1999) and such architects should also be able to assess the energy performance of the building they are designing using a relatively simple calculation.

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