Life Cycle Optimization of Extremely Low Energy Dwellings

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ABSTRACT: A global methodology is developed to optimize concepts for extremely low energy dwellings, taking into account energy use, environmental impact, and financial costs over the life cycle of the buildings. Energy simulations are executed with TRNSYS. The ecological impact is evaluated through a life cycle inventory of the whole building, whereas costs are evaluated through a cost-benefit analysis. The multi-objective optimization problem is tackled by combining genetic algorithms and the Pareto concept. First, the optimization methodology is presented. Subsequently, the validity as well as the strengths and weaknesses of the methodology are discussed. Finally, the main results are presented followed by a discussion of the trade-off curves of primary energy consumption and net present value, an analysis of the embodied energy, and a study of the impact of economic parameters, such as price evolutions above inflation and discount rate.

KEY WORDS: multi-objective optimization, genetic algorithms, life cycle inventory, extremely low energy dwellings, economic trade-off.

INTRODUCTION

SINCE THE OIL crisis of the early seventies, energy consumption in buildings has become an important concern. During the early years, most research focused on the reduction of transmission losses, later combined with an optimization of passive solar gains. The next step was...
the search for better performing heating systems, such as condensing boilers and heat pumps, and the reduction of ventilation losses through heat recovery systems. From the early nineties, the interest slowly shifted towards the overall sustainability of buildings, not only focusing on the consumption of non-renewable resources during the usage phase, but also taking into account the environmental impact during the whole life cycle of the building (Anon., 1999).

Many national and international initiatives have been launched since then to improve energy efficiency and sustainability in buildings (IEA-ECBCS, EU Frame Programs, ...). One of the current trends concerns the development of extremely low energy dwellings. This ranges from passive houses aiming at such a low net heat demand that a traditional heating system is no longer necessary (CEPHEUS; Feist, 2006, www.passivhouse.com) and zero energy houses in which the self-generated energy production needs to cover their own energy consumption on a yearly basis (Comer et al., 2000; Christian et al., 2004; DOE) to energy autarkic buildings, which are completely disconnected from any external supply net and have their own local sustainable supplies for energy and water. These concepts tend to be considered as the ultimate objectives for sustainable buildings (Comer et al., 2000). In contrast with traditional buildings, these approaches assume the application of a good many technologies resulting not only in much more embodied energy and more embodied pollution, but also more resources to produce and maintain these technologies and much more costs to construct these buildings. Although these buildings have much smaller energy consumption during the usage phase, the projects hardly ever show clearly if the global balance of energy, ecology, and costs is finally positive.

An important tool for evaluation and quantification of global environmental impact is life cycle assessment (LCA) (Jensen et al., 1998). However, since LCA traditionally originates from the chemical and packaging industry, it is mostly concerned with materials, components, and product design. Rarely have buildings as a whole been subject to detailed LCA. Furthermore, LCA is mainly used as an instrument to quantify inflows and outflows and environmental impacts, but it lacks the ability to be used as an instrument to optimize decision making (Gayk, 1996; Erlandsson et al., 1997; Hasan, 1999; Borjesson and Gustavsson, 2000).

Furthermore, global optimization of a building as a whole is a complex optimization problem due to the number of parameters and variables, the non-linear relations between variables and second-order effects. During the last two decades, evolutionary computation techniques, such as genetic algorithms (GA), have been receiving increasing attention regarding their potential as optimization techniques for such complex problems (Michalewicz et al., 1996). They are adaptive optimization methods, inspired
by the genetic processes of biological organisms. Over many generations, natural populations evolve according to the principles of natural selection and ‘survival of the fittest’. By mimicking this process, evolutionary computation is able to evolve solutions to real world problems (Beasley et al., 1993; Asiedu et al., 2000; Craw, 2002). One of their main advantages is that they do not require much mathematical detail for solving optimization problems (Michalewicz et al., 1996). However, application of these techniques to building-related engineering is still rare (Asiedu et al., 2000; Wang and Jin, 2000; Wang et al., 2005a,b).

So, what is missing in the current trends for sustainable buildings is an underlying global methodology to develop and evaluate on a scientific basis residential buildings that are globally optimized from the viewpoint of energy use, ecological impacts, and costs. The development and implementation of this methodology has been the subject of the research project presented here. Basic principles for this methodology involved a well-founded evaluation of the environmental impact and financial costs during the whole life cycle of the building and its installations, by coupling LCA and cost assessment with advanced optimization techniques. This resulted in concepts and guidelines for globally optimized buildings. Because of the large scope of the research project and the enormous amount of results, only part of the results can be presented here. The focus of this study is mainly on the trade-off between energy and costs for (extremely) low energy dwellings, the hierarchy of energy saving measures that could be deduced from this trade-off, and the relation of embodied energy to energy savings for these dwellings.

METHODOLOGY

The methodology consists of three pillars; each is presented in the following paragraphs. The first pillar is represented by the optimization strategy. It concerns multi-objective optimization that combines the technique of GA with the Pareto concept. The two other pillars consist of the model for life cycle inventory (LCI) for buildings as a whole and of the model for cost assessment.

Multi-objective Optimization

Reference Buildings

The objects for optimization are residential buildings. As the methodology is developed for Belgian building practice, several representative
reference dwellings have been designed, with a fixed geometry for the non-insulated version. This means that the configuration of the building and dimensions of the rooms were not objects for optimization. Only the glass area per room could vary in order to include the impact of the glass area on the net heat demand and summer comfort. The results that will be discussed in this study are those for a typical terraced dwelling. Plans and façades of the building can be found in Annex A.

Energy Saving Measures

The parameters for optimization are related to the energy saving measures, which were always applied to both the building envelope and the heating system. The optimization itself is performed in two steps. In the first step, only envelope-related energy saving measures were considered, such as the amount of insulation used, use of better glazing, glass area, sun shading, air tightness, and natural ventilation scenarios.

Insulation measures were taken for the roofs, attic floor, façade, and ground floor. The insulation thickness in each envelope component varied from zero to a maximum and different types of insulation material could be applied. Table 1 gives the maximum insulation thickness per envelope component, as well as the applicable materials.

The glazing types were selected from the window library of PREBID, the building description interface of TRNSYS that contains 66 different glazing types with a U-value varying from 2.8 to 0.4 W/m²K and a g-value varying from 0.76 to 0.21. For calculating the edge correction of the U-value of the glazing, five spacer types are available in PREBID. A choice list of window

Table 1. Details on the insulation measures: maximum thickness and applicable materials per envelope component.

<table>
<thead>
<tr>
<th>Envelope component</th>
<th>Maximum thickness (cm)</th>
<th>Applicable materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat roof</td>
<td>30</td>
<td>MW, PUR, CG</td>
</tr>
<tr>
<td>Sloped roof</td>
<td>40</td>
<td>MW, PUR, EPS, XPS, CF</td>
</tr>
<tr>
<td>Attic floor</td>
<td>40</td>
<td>MW, PUR, EPS, XPS</td>
</tr>
<tr>
<td>Façade</td>
<td>30</td>
<td>MW, PUR, EPS, XPS</td>
</tr>
<tr>
<td>Cavity wall or external insulation</td>
<td>30</td>
<td>MW, PUR, EPS, XPS</td>
</tr>
<tr>
<td>Wood frame construction</td>
<td>30</td>
<td>MW, CF</td>
</tr>
<tr>
<td>Floor</td>
<td>15</td>
<td>MW, PUR, EPS, XPS</td>
</tr>
</tbody>
</table>

MW = mineral wool, PUR = polyurethane, CG = cellular glass, EPS = expanded polystyrene, XPS = extruded polystyrene, CF = cellulose fiber.
frames is based on (WTCB 1999; Passivhaus) that contains window frames of wood, PUR, PVC, and/or aluminum with a U-value varying from 6 to 0.65 W/m²K, including frames that meet the standard for passive housing. The glass area could vary per window between a minimum and a maximum value. Minimum and maximum were defined per room, depending on the minimum requirement for light intensity and the constructional limitations of the façade. To control summer comfort, it was possible to add a movable internal or external shading with an opaque fraction \((1 - \tau)\) of 0–100%. If the option of shading was selected, it was applied to all windows with a south to west orientation and controlled by the indoor temperature in each room.

Four levels of air tightness were considered, being the average hourly air change rate at 50 Pa pressurization \((n_{50})\) of newly built dwellings (SENVIVV, 1998), \(n_{50} = 3/h\) (standard for a well-designed natural ventilation system), \(n_{50} = 1/h\) (standard for mechanical ventilation), or \(n_{50} = 0.6/h\) (standard for passive houses). Finally, four ventilation scenarios were considered to analyze the impact of extra summer or night ventilation as an extra measure to control summer comfort.

Initially, the thermal capacity was set as one of the variables for optimization. This way, massive and lightweight construction variants could be mutually compared. However, based on the original assumptions, wood frame construction was favored for two of three objectives, namely embodied energy and investment costs and therefore, obviously, most of the optimal solutions comprised lightweight constructions. However, since wood frame constructions are still rare in Belgium, the uncertainty on the investment costs for wood frame construction was much higher than that for massive constructions. Furthermore, in Belgium, where the majority of the dwellings are built with cavity walls, and brick production forms an essential part of the industrial activities, it is highly unrealistic, and from the point of view of the building sector not opportune, to promote a total shift of the building sector towards only wood frame constructions. Therefore, the thermal capacity was no longer considered as a parameter to be optimized. Obviously, it still has been considered as an impact parameter for energy use, but the optimization process has been executed separately for each of the construction types (cavity wall, massive wall with outer insulation, and wood frame construction). This created the possibility to deduce optimized low energy concepts for each of the construction types.

The first step in the optimization process resulted in concepts for optimized building envelopes for net heat demand, investment costs, and environmental impact. Only for these concepts, the second optimization step was performed.
In the second step of the optimization process, the measures on the building envelope were combined with system-related measures. This included systems for distribution, emission, production and storage of heat, systems for local electricity production, and control systems. The traditional measures have been considered, such as high efficiency or condensing boilers using natural gas or fuel oil, but the aim of the project was to pay more attention to new technologies, such as different types of heat pumps (air-to-water and ground-to-water) and systems for cogeneration of heat and power (CHP). No local space heating systems have been considered. The heat was assumed to be emitted by radiators with or without a rear radiation shield, convectors, low temperature radiators, or floor heating. The room temperature could be controlled by a thermostat or thermostatic valves. The exit temperature of the water in the boiler could be fixed or variable. In order to simulate passive house concepts, the combination of a mechanical ventilation system with heat recovery and integrated electrical heating was also incorporated into the listed choice of heating systems.

In the first step of the optimization process, a natural ventilation system has been assumed, whereas in the second optimization step, four extra ventilation systems were simulated with the corresponding levels of air tightness. For all ventilation systems, the ventilation flows were calculated according to the ruling ventilation standard (NBN D50-001, 1991). The following ventilation systems were considered:

- a properly designed natural ventilation system with self-regulating grids that reduce their ventilation opening when air pressure differences higher than 2Pa are reached, in order to avoid unnecessary high ventilation losses;
- mechanical extraction ventilation with natural supply through self-regulating grids and extraction with a DC ventilator;
- mechanical supply and extraction, with a DC ventilator and without heat recovery;
- mechanical supply and extraction, with a DC ventilator and with a heat recovery unit. Different levels of efficiency of heat recovery have been considered (50, 70, and 90%). This way, both the quality of the recovery unit as well as its effectiveness can be evaluated.

Also thermal solar collectors and photovoltaic systems have been considered in the second phase. However, their impact will not be discussed here.

The methodology could easily be adapted to optimize all energy saving measures simultaneously, but this option was not applied. After all, the building envelope can be considered as the hardware of the building, due to
its long life span in comparison with most components of the heating system. The heating system then corresponds to the midware of the building in terms of its longevity. Because of the long lasting impact of decisions concerning the building envelope on the energy performance of a building, it is preferable to first optimize the building envelope, i.e., minimize the net heat demand in a cost-effective and ecologically optimal way. Subsequently, the most appropriate heating systems for this low net heat demand can be identified. This way, the logical hierarchy of energy saving measures that has already been deduced in an earlier work, is respected (Verbeeck and Hens, 2005).

Multi-objective Evolutionary Optimization Technique

The optimization of extremely low energy dwellings is an optimization problem that involves a large number of parameters, variables, and constraints. It also is a multi-objective optimization problem, as energy, ecology, and costs need to be optimized simultaneously.

To deal with the large number of variables, the optimization method of GA was selected. The algorithm starts from a set of individuals called a population, in which each individual, called a chromosome, represents a possible solution to the problem. Solutions from one population are selected to create a new population. Solutions that are selected (=parents) to form new solutions (=offspring) are selected according to their fitness, which means the more suitable they are for the problem, the higher their probability to be selected for reproduction (Dasgupta and Michalewicz, 1997; Obitko, 1998). In this way the new population is normally an improved population.

Applied to the reference buildings, each potential variant of these buildings was represented unequivocally as a set of parameters, joined together in a string of values. This string forms the chromosome, in which each value represented one variable, being the insulation thickness in the roof, the façade or the floor, glazing type, type of sun shading, glass area, etc. for a particular building design. The fitness of a solution depended on its primary energy consumption, net present value (NPV), and global warming potential.

While the concept of GAs is suitable to deal with the optimization of multiple variables, the Pareto concept suits for the simultaneous optimization of multiple objectives (Fonseca and Fleming, 1995; Coello, 1999; Gens, 2001). This concept treats all objectives equally during optimization and deduces the trade-off between objectives by determining the non-dominated solutions. A solution is non-dominated or Pareto optimal if no other feasible solution exists that decreases one objective without causing simultaneously
an increase in at least one other objective. For two objectives this results in a curve of non-dominated solutions (Pareto curve), for three objectives a surface of non-dominated solutions (Pareto surface) results. Pareto optimization for more than three objectives is possible, but visualization is not evident (Pohlheim, 1999).

During the optimization process, each solution in a population was ranked according to its fitness for the three objectives. The ranking was based on the Pareto score of the solution, being the number of solutions in the population by which the solution was dominated. Non-dominated solutions have score 0. Constraints, such as summer comfort and insulation standard, were treated through a penalty function. If one or two constraints were not met, a penalty was added to the Pareto score, proportional to how much the constraint was exceeded.

The Pareto concept contrasts with the single-objective optimization technique that is used sometimes to deal with multiple objectives. In single-objective optimization, the different objectives are aggregated into one single objective by a weighted sum approach and each optimization run results in one single optimum, only valid for the selected weighting factors. By use of the Pareto concept and combining it with the technique of GAs, the optimization run does not result in one single optimum, but in the trade-off between the objectives. This way, all information on the objectives is maintained during the optimization and no weighting has to be done prior to the optimization process. With this technique, the weighting of the objectives can be postponed to the decision process that follows the optimization process. This way, the same results can serve to deduce different decision strategies for different target groups, by weighting one objective as more important than the others, depending on the target group.

Life Cycle Inventory Model for Buildings

**GOAL AND SCOPE**

As explained earlier, the global methodology, presented here, is a tool to develop extremely low energy buildings that are optimized over their life cycle for energy use, costs, and ecological impact. Therefore, the energy use and ecological impact from all life cycle phases needed to be incorporated in the optimization process. This required the establishment of a calculation model for the ecological impact that could be integrated in the optimization model. Life cycle assessment according to ISO 14040 (1997) normally consists of a LCI, being an inventory of all inflows and outflows, followed by a life cycle impact assessment (LCIA), in which the contributions from the different inflows and outflows to impact categories, such as climate change, human health, ecosystem quality, etc. are calculated.
However, because of the uncertainties coupled to the models for calculating impact indicators, the LCA here was mainly limited to a LCI of energy flows and emissions. No impact indicators were considered, except for the global warming potential that calculates the cumulative climate change effect of the different emissions over a certain period.

As the optimization process is aimed at developing building concepts that are globally optimized and at the same time satisfy the boundary conditions for thermal comfort, visual comfort, indoor air quality, etc., the LCI did not focus on materials or building components, but considered the building as a whole. However, some of the basic assumptions of traditional LCI cannot cope with the characteristics of buildings. Owing to the very long lifetime of buildings (80 years and more) hypotheses on processes involving the end phase, such as waste management and recycling, might result in highly uncertain and even unrealistic results. At the same time, before reaching its end of life, most buildings have been undergoing several refurbishments or renovations, often resulting in thorough modifications of the building. Therefore, this research did not concentrate on the whole life span of the building, but considered only the impact of one generation. This resulted in the scenario that the building is designed, constructed, and then used and maintained by one generation for 30–40 years. Thus the phases of extraction, production, transport, usage, and replacement were taken into account, whereas the end phase of the building was not considered.

The primary goal of the LCI was, therefore, to establish a LCI database for building-related materials and components and to develop a LCI model for the building as a whole that could be incorporated in the optimization process. Furthermore, this LCI created the opportunity to analyze the relation between the energy savings realized with extremely low energy building concepts and the embodied energy needed to create these building concepts. The balance between embodied energy and energy savings should always remain positive over the life cycle of the building. Otherwise, the goal of developing sustainable buildings will not be met. The energy flows from all phases and the corresponding emissions could easily be summed up to create energy related and ecology related optimization criteria, such as the total primary energy consumption and the total global warming potential.

**INPUT DATA AND INVENTORY MODELS**

All LCI data were extracted from the Ecoinvent2000 database (Frischknecht, 2003). It is currently the most extensive and most complete database of this type, with representative data for Western Europe, including Belgium, and it is frequently updated. Not all 2500 process datasets from the Ecoinvent database were of interest for this research. Forty-seven datasets for building related processes were extracted to
calculate the LCI of 54 building related commodities. In the same way not all elementary flows were extracted. They were limited to energy resources, waste heat, and emissions of CO$_2$, NO$_x$, SO$_x$, non-methane VOCs and particulates. Extraction of the impact indicators was limited to the global warming potential for a time frame of 20, 100, and 500 years, being the cumulative climate change effect of the emissions over a 20, 100, and 500 year period. Details on the underlying assumptions of the data from the Ecoinvent2000 database can be found in Frischknecht and Jungbluth (2003).

The energy consumption and emissions related to the building were calculated for the different subsequent phases, as shown in Figure 1. For each phase, calculation models were developed, as described below.

For the exploitation and production phase, the Ecoinvent database provided the main input. Several materials used within the project, such as brick, concrete, plywood, rock wool, etc. correspond directly to materials defined in the Ecoinvent database and thus, the inventory data could directly be imported from Ecoinvent. For other commodities, such as hardwood or softwood, window frames, sun shading, or installation components, inventory data from different Ecoinvent datasets need to be combined based on a material or product model. At the end of the production phase materials or products were assumed to be stored at the production plant, ready for transport.

For the transport phase, distinction was made between the transport of construction material and transport of installation components.
For the construction materials, distinction was made between transport from the production plant to the distribution or assemblage center (Step 1) and from there to the construction site (Step 2). For the installation components Step 1 always assumed transport of the composing materials to the assemblage site, whereas Step 2 reflected transport of the finished goods to the construction site. For each transport step, assumptions were made for each material or product on transport distance, transport vehicle, and transport weight. Based on these assumptions, the overall energy consumption and emissions due to transport were calculated.

A more detailed description of the material and product models and of the assumptions for the transport model can be found in (Verbeeck, 2007).

Based on the data of these two phases, a straightforward calculation algorithm was developed to calculate the LCI data for a whole building:

1. Basic matrices are composed, containing data on embodied energy, embodied emissions, transport energy, and transport emissions for all basic constructional materials and installation related materials.

2. With the basic matrices a MATERIAL matrix is calculated containing the global data for production and transport of each construction material in the project database. In the same way an INSTALLATION matrix is calculated containing the global data for production and transport of each installation component.

3. For each variant of the reference building the applied volume, area, or length per constructional material is calculated and stored in a VOLUME matrix. The installation power is determined from the insulation level. Lengths of heating pipes and ventilation pipes and the number of radiators depend on the type of reference building. Different volume matrices are calculated for different usage periods, taking into account replacements of materials and products based on assumptions of life span for each material, product, or installation component. The following assumptions were made on life span: 20 years for windows with double glazing and for ventilation grids, 10 years for sun shading, 20–25 years for heat production systems, 10 years for pumps, ventilators, and control systems, no replacements within 40 years for any construction elements or emission and distribution components.

4. Based on the MATERIAL and the VOLUME matrix and the information on the installation, results on waste heat, energy content, non-renewable energy demand, GWP_{100}, NO_x, SO_x, NMVOC, and particulates <2.5 μm are calculated for the whole building variant for production and transport of both constructional materials and installation components.
5. For each building variant the yearly net heat demand, yearly end energy consumption, yearly primary energy consumption, and yearly GWP\textsubscript{100} are calculated with the dynamic building simulation program TRNSYS.

6. The primary energy consumption and GWP\textsubscript{100} is calculated for the use phase, assuming use of the building by one generation for 30 years.

7. In a final step the non-renewable energy consumption as well as the GWP\textsubscript{100} is summed up for production, transport, and usage. These values are applied as energy related criterion and ecological criterion in the optimization process. The other flows do not interfere with the optimization, but can serve as extra information for the final decision making process.

8. No assumptions have been made on the destination of the building and its composing materials after passing from one generation to the next.

\textbf{PERTURBATION AND UNCERTAINTY ANALYSIS}

Despite the straightforwardness of the building model and the inventory algorithm, the uncertainty is quite high, since all matrices of the building model contain data based on more or less uncertain assumptions. Therefore, a sensitivity and uncertainty analysis was performed on the partial models and on the LCI model for the building as a whole. Owing to a lack of detailed information on the uncertainty of the inventory data, the sensitivity of the inventory model for errors and error propagation was analyzed by conducting a perturbation analysis as well as an uncertainty analysis by Monte Carlo simulations.

According to Heijungs et al. (2005) a perturbation analysis identifies the sensitive parameters, being the input parameters of which a small change induces a large change in the selected results. The advantage of a perturbation analysis is that it allows studying inherent sensitivities, even for variables for which no uncertainty indication is known. Perturbations of 1\% of each value successively were induced in all composing matrices of the calculation algorithm. Apparently, most impact is realized through perturbation of data related to wood or wood derivatives, such as plywood and wooden window frames. Furthermore, the sensitive categories are the waste heat balance and the global warming potential. These are exactly the categories for which wood acts differently from other building materials. The waste heat balance for renewable materials, such as wood, is negative, as the energy content of the material (biomass) has not been used at the stage of production, but is already counted for within the waste heat balance. Also the global warming potential of wood is negative in contrast to other materials, due to the uptake of CO\textsubscript{2} emissions during the growth phase of the trees. However, due to the linearity of the building LCI model,
the perturbation of a single parameter has generally little impact on the overall result and thus no inherent sensitivities exist.

However in practice, uncertainties exist for all data and by propagation, the uncertainty on the final result may become large. This was analyzed through an uncertainty analysis with Monte Carlo simulation. For most input data only one value is known with no quantitative information on the uncertainty in terms of standard deviation. The known value was therefore assumed to be the mean value. A normal distribution was assumed for the input data. Several scenarios were selected for the coefficients of variance (=standard deviation/mean value), thus providing assumptions for the standard deviation and for the width of the distribution curve of the input data. As a first step, the same variance coefficient was selected for all input data and the coefficients of variance for the output data were calculated through 1000 Monte Carlo simulation runs. An uncertainty analysis was made for variance coefficients of 5, 20, 50, and 100%. In a second step, the variance coefficient was set at 5% for all input matrices, except for one matrix for which the coefficient of variance was set at 30%. First, an uncertainty analysis was performed on the LCI model of the construction, then on the LCI model of the installations and finally, on the LCI model of the building as a whole. The Monte Carlo simulation showed that the propagation of errors is limited and that the errors of the different input data neutralize each other somehow. Analysis of the LCI model of the construction showed that only for wood frame construction, the errors on the GWP of the different input data were propagated more intensively, because of the negative global warming potential for wood and wood-derived products. For non-renewable embodied energy, this was not the case, since the embodied energy is positive for all materials. In the installation model, the input data for both the non-renewable embodied energy and the global warming potential are positive and therefore, the results obtained for both objectives were comparable. Analysis of the LCI model of the building as a whole showed that by adding the positive GWP related to the installation to the GWP of the building construction, the difference between the results including and excluding wood frame constructions for the overall building was smaller than in case only the constructional part of the building is analyzed.

From both sensitivity studies it was concluded that the sensitivity for errors and the propagation of errors is limited and that the errors of the different input data neutralize each other somehow. Errors on input data related to material properties have the highest impact, whereas errors on transport-related input data only have a minor impact on the overall uncertainty.
Cost Assessment

COST CRITERIA

To evaluate the economic impact of the building concepts from the point of view of a private building owner, a cost-benefit analysis was integrated in the optimization model. This required the establishment of a cost database and a cost evaluation model.

In the cost evaluation module a large number of economic criteria was calculated and stored. This created not only opportunities for an in-depth analysis of the results i.e., to compare the contribution of constructional measures versus installation measures to the overall cost, and to compare total costs versus extra costs, etc. It also provided a basis for evaluating the different economic evaluation criteria and to determine the best criterion to be incorporated into the optimization process. The following criteria were calculated for each building variant:

- Initial investment costs, being the total investment costs for the building envelope and for the installation components.
- Investment cost for replacements within the usage period of the building.
- Yearly maintenance costs for the heating system and the mechanical ventilation system.
- Yearly energy costs for fossil fuels and electricity, only related to the building and its equipment for heating, domestic hot water, and ventilation. No electricity consumption for domestic electrical appliance use or lighting was included.
- Total present value and NPV, based on assumptions for usage period, discount rate, and price evolutions. For the total present value, all total costs within the considered usage period are discounted, whereas for the NPV, extra costs and energy cost savings, compared to a reference, are discounted. The non-insulated version of the dwellings serves as the reference.

Although the cost evaluation module calculates and stores a large number of economic criteria, only one cost criterion could be incorporated in the optimization process. As explained above, the optimization was always performed in two steps. In the first step, only energy saving measures related to the building envelope were considered, whereas in the second step installation related variables were optimized.

As in the first step only the net heat demand was calculated and no assumptions were made as to the heating system used, there was in this phase not enough information available to calculate the yearly energy cost. Therefore, only the initial investment cost could serve as cost criterion in this phase. In the second phase when the heating system was defined,
the yearly energy consumption and the yearly energy cost could be calculated.

However, there still remained the choice between the total cost of the buildings and the extra costs compared to the reference as the most appropriate economic optimization parameter. Comparing the optimization process for the criterion of total present value and for the criterion of NPV revealed that the same results were obtained with both criteria. So, the total present value was chosen as the optimization criterion, but for the interpretation of the results, the focus is laid on the NPV, as only solutions with a positive NPV can be considered economically viable.

**COST DATABASE**

The cost database was mainly established with cost data provided by building contractors that were found willing to make a price offer for the reference buildings. The price offers comprised the working hour cost. With these data a cost database was created that allowed one to calculate the overall construction cost of a building with massive walls, cavity walls, or wood frame construction. The database was structured in a way that the costs for replacement of components could be easily extracted as separate data.

The cost data for installation components are also based on up to date (from 2005) price information for boilers, radiators, convectors, floor heating systems, storage tanks, fans, pipes, etc. As the dimensions of the heating system strongly depend on the insulation level and on the type of building, a detailed dimensioning of the heating system for each building variant according to the ruling standards would be necessary. However this approach is infeasible within an optimization method. Therefore, cost curves were determined for each reference building that express the cost of the heating system as a function of the insulation level. These cost curves are based on a detailed analysis of seven insulation levels per reference building (Hens, 2005).

**ENERGY PRICES AND PRICE EVOLUTION**

The assumptions for energy prices were based on private consumer prices. For electricity and natural gas, the adopted prices came from the Federal Ministry of Economic Affairs; for fuel oil, the adopted price came from Informazout, the Belgian organization of fuel distributors, and was valid for a purchase of more than 2000L of fuel oil. Table 2 presents the energy prices. The prices for electricity and gas include taxes for transport, distribution, energy taxes, and federal taxes.

For the price evolution of gas, fuel oil, and electricity, three different scenarios were used: a low, medium, and high scenario. The values for the
medium and high scenario concern price evolution above inflation and are based on the EU POLES scenarios from 2000 until 2030 for gas and fuel oil (EU, 2004). The values are presented in Table 3.

### Energy Simulations and Boundary Conditions

The energy simulations were executed with TRNSYS, a transient systems simulation program with a modular structure (TRNSYS, 2005). The input data for ventilation and infiltration were calculated with (COMIS, 2003). This multizone infiltration and ventilation simulation model predicts the airflows in and through the building, taking into account both internal and external boundary conditions. COMIS can easily be coupled with TRNSYS. All boundary conditions need to be specified as input data in TRNSYS. For the internal gains, a household scenario was specified for a household of two persons of which one adult stays at home. This scenario describes the occupancy and use of lighting and electrical appliances in each room for each hour of a week- or weekend-day and thus determines the internal gains and the set temperature for each room. The weather data were hourly average data for the Test Reference Year of Brussels, Belgium. The risk for summer overheating was evaluated with the method of weighted temperature exceeding hours (WTE-hours) according to (ISSO/SBR, 1994). This Dutch method, developed for the assessment of summer comfort in office buildings, was adapted for dwellings, based on (Maeyens, 2001). The limit for summer comfort was set at 130 WTE-hours per room.

### Table 2. Proportional and fixed term of the energy price for the energy carriers.

<table>
<thead>
<tr>
<th>Energy prices</th>
<th>Natural gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional term (c€/kWh)</td>
<td>4.64</td>
<td>18.33</td>
</tr>
<tr>
<td>Fixed term (€/year)</td>
<td>103.46</td>
<td>40.40</td>
</tr>
</tbody>
</table>

### Table 3. Three scenarios for the evolution of the energy prices in % per year.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Low % per year</th>
<th>Medium % per year</th>
<th>High % per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>0</td>
<td>2.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>0</td>
<td>1.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>2.1</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Outline of the Program

The program for the global methodology, including the GA program was written in MATLAB. The advantage of using MATLAB is the easy coupling between a main MATLAB program and other programs, such as building simulation programs or spreadsheet programs with databases for costs and LCI. Figure 2 shows the scheme of the program for the overall optimization methodology.

![Diagram of the program](image)

**Figure 2. Outline of the global optimization methodology.**
Validation of the Program

In an earlier work on energy saving renovation of residential buildings (Verbeeck and Hens, 2002) all possible combinations of energy saving measures on the building envelope and the installations have been calculated for five reference dwellings (around 4000 combinations per dwelling). Calculations were executed with the steady-state energy performance for buildings (EPB, 2005) program and the results were then sorted in EXCEL to obtain the most optimal solution. To validate the developed multi-objective optimization methodology, the same five dwellings were optimized considering the same energy saving measures and using the building simulation program, cost and LCI database from the earlier project. The advantage of validating with these results is the short calculation time of the EPB program (1 s per building variant vs. 1 min with TRNSYS) and the fact that the optima to be found were known a priori. In the final methodology, however, the dynamic building simulation program TRNSYS has been used instead of steady-state EPB program because of the ability to simulate the dynamic effects and interactions of installations and ventilation more correctly. The developed optimization program proved to result in the same optima as found through calculating all combinations.

RESULTS

Optimization of the Building Envelope Measures

The assessment and optimization criteria within the project were energy use, ecological impact, and costs. In the first phase, only measures on the building envelope were considered and heating systems were not yet included; primary energy consumption was only calculated in the next phase. Therefore, the impact of the measures on energy was assessed through the yearly net energy demand for heating and the embodied non-renewable energy of the whole building.

Plans and façades of the terraced reference house are given in Annex A, whereas Table 4 gives the values for net energy demand, non-renewable embodied energy, and investment cost for the reference versions of the terraced house. Distinction has been made between a reference version with a non-insulated cavity wall, a non-insulated massive brick wall as used for outer insulation systems, and a wood frame structure. For the latter, 8 cm of mineral wool was included, as this construction type is never used without insulation. Obviously, this resulted in a lower net energy demand for the reference situation in the case of a wood frame structure.
Table 5 presents the results for the first step of the optimization process, being the optimization of the building envelope. First, the number of optimal solutions found with the optimization process is shown. Then for each case, the range is given in which the optimal solutions lie.

For the net heat demand two results are presented for the following reason: for the development of extremely low energy concepts, heat recovery of ventilation losses is indispensable to minimize the net heat demand. However, this needs the presence of a heat recovery unit, which was only implemented in the second step of the optimization process. To incorporate the impact of heat recovery in the optimization of the net heat demand, two results are given: the net heat demand without recovery of ventilation losses and the net heat demand, assuming a heat recovery efficiency of 70%. As can be noticed from Table 4, this has a significant impact on the net heat demand. Depending on the magnitude of the heat losses versus the heat gains and the contribution of the ventilation losses to the overall net energy demand, the benefits of heat recovery can be substantial.

### Table 4. Reference values for the terraced reference house per constructional type.

<table>
<thead>
<tr>
<th>Terraced house</th>
<th>Net energy demand (MJ/m³a)</th>
<th>Non-renewable embodied energy (MJ/m³)</th>
<th>Investment cost (€/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity wall</td>
<td>184</td>
<td>560</td>
<td>740</td>
</tr>
<tr>
<td>Massive wall</td>
<td>215</td>
<td>565</td>
<td>710</td>
</tr>
<tr>
<td>Wood frame construction</td>
<td>136</td>
<td>600</td>
<td>740</td>
</tr>
</tbody>
</table>

### Table 5. Results for the optimization of the building envelope.

<table>
<thead>
<tr>
<th></th>
<th>Terraced house</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of optimal solutions</td>
<td>44</td>
</tr>
<tr>
<td>Insulation level</td>
<td>K14-40</td>
</tr>
<tr>
<td>$U_{\text{mean}}$ (W/m²K)</td>
<td>0.19–0.54</td>
</tr>
<tr>
<td>Glass area (m²)</td>
<td>25–56</td>
</tr>
<tr>
<td>Average% of floor area</td>
<td>20%</td>
</tr>
<tr>
<td>Net energy demand (MJ/m³a)</td>
<td></td>
</tr>
<tr>
<td>Without heat recovery</td>
<td>50–100</td>
</tr>
<tr>
<td>With 70% recovery of ventilation</td>
<td>20–70</td>
</tr>
<tr>
<td>Non-renewable embodied energy (MJ/m²)</td>
<td>630–900</td>
</tr>
<tr>
<td>±10%</td>
<td></td>
</tr>
<tr>
<td>Embodied GWP (kg/m³)</td>
<td>25–90</td>
</tr>
<tr>
<td>±10–30%</td>
<td></td>
</tr>
<tr>
<td>Investment cost (€/m² floor area)</td>
<td>800–1100</td>
</tr>
</tbody>
</table>
demand, recovery of 70% of the ventilation losses could reduce the net energy demand with 30–60%.

Globally Optimized Concepts

Figures 3 and 4 present the optimal solutions from the second step of optimization process for the terraced dwelling. Figure 3 gives the NPV as a function of the total primary energy consumption over the usage period for the low energy price scenario (no price increase above inflation), whereas Figure 4 gives the same results for the high energy price scenario (+3–4% price increase above inflation, see Table 3). The results are valid for a usage period of 30 years and a discount rate of 4% above inflation. According to the Pareto concept, the optimal solutions were determined by determining the trade-off curve (=optimal solutions) for the three objectives: the total or NPV over 30 years, the GWP over 30 years and the primary energy consumption over 30 years. In Figure 3, all results that have been calculated are presented as gray squares, whereas the trade-off curves are presented as black dots. Distinction has been made between optimal solutions with a positive NPV (solid black dots) and optimal solutions with a negative NPV.
The latter are part of the trade-off curve, but are not economically viable for the assumptions made.

Some optimal solutions in Figures 3 and 4 seem to be suboptimal as solutions exist with higher NPV for the same total primary energy consumption. They are nevertheless part of the trade-off curve. This misleading visual effect is caused by the fact that the optimization process considers three objectives (NPV, total primary energy consumption, and GWP), whereas the figure only shows two objectives. The actual trade-off is a 3D surface and the optimal solutions in Figures 3 and 4 (black dots) are in fact a 2D projection of that 3D trade-off surface. This projection does not coincide completely with the 2D trade-off curve of NPV and total primary energy consumption. This explains why some optimal results in Figures 3 and 4 lie below the 2D trade-off curve.

Obviously, the optima with a positive NPV are of most interest, as they are economically viable. In Figure 3 they are even viable in the improbable case that the energy prices remain constant (above inflation). Comparison of Figures 3 and 4 shows that the trade-off curve in both figures almost contains the same solutions, being for Figure 3:

A. $U = 0.36 \text{W/m}^2\text{K} + \text{high efficiency boiler} + \text{natural ventilation with no attention for the air tightness}$

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**Figure 4.** Terraced house, usage period of 30 years, high energy price scenario, discount rate = 4%: the NPV over 30 years (NPV30) is given as a function of the total primary energy consumption. All results are presented in gray, whereas the trade-off curve is given in black. The solid black dots have a NPV30 $> 0$. 

Downloaded from http://jen.sagepub.com by on November 10, 2009
Almost the same hierarchy of solutions is found for the high energy price scenario in Figure 4:

A. \( U = 0.36 \, \text{W/m}^2\text{K} + \text{high efficiency boiler + natural ventilation} \)
B. \( U = 0.34 \, \text{W/m}^2\text{K} + \text{high efficiency boiler + natural ventilation} \)
C. (this combination is not part of the trade-off curve for the high energy scenario)
D. \( U = 0.34 \, \text{W/m}^2\text{K} + \text{air-to-water heat pump + natural ventilation} \)
E. \( U = 0.34 \, \text{W/m}^2\text{K} + \text{high efficiency boiler + ventilation with heat recovery + air tightness } n_{50} = 0.6/\text{h} \)
F. \( U = 0.28 \, \text{W/m}^2\text{K} + \text{high efficiency boiler + ventilation with heat recovery + } n_{50} = 0.6/\text{h} \)
G. \( U = 0.20 \, \text{W/m}^2\text{K} + \text{high efficiency boiler + ventilation with heat recovery + } n_{50} = 0.6/\text{h} \)
H. \( U = 0.20 \, \text{W/m}^2\text{K} + \text{condensing boiler + ventilation with heat recovery + } n_{50} = 0.6/\text{h} \)
I. \( U = 0.28 \, \text{W/m}^2\text{K} + \text{ground-to-water heat pump + ventilation with heat recovery + } n_{50} = 0.6/\text{h} \)
J. \( U = 0.20 \, \text{W/m}^2\text{K} + \text{CHP + ventilation with heat recovery + } n_{50} = 0.6/\text{h} \)

To show the role of the third objective in the optimization results, Figure 5 presents the same results and the same optima as Figure 4, but now for the objectives ‘NPV’ and ‘GWP’. Where the optima in Figure 4 between points F and J have an energy consumption between 880 and 980 GJ, the range for the GWP for these optima is relatively wider, from 39 to 50 ton,
mainly because of differences in energy carrier: F and G are boilers on fuel oil, I a heat pump on electricity whereas H and J use gas.

Similar results have been found for other building types, such as a semi-detached house, a compact detached house, a fragmented detached house, and a flat (Verbeeck et al., 2007), but to keep the scope of this study under control, only results for the terraced house are presented here.

Of great importance is that the results of this extensive research project reaffirm the hierarchy of energy saving measures that was already determined in earlier, less extensive research projects (De Coninck and Verbeeck, 2005; Verbeeck and Hens, 2005). This hierarchy consists of the following steps of most cost-effective energy saving measures:

1. First, investing in a good insulation level with good air tightness and a well-designed natural ventilation system (Point B in Figure 3). The insulation level in Flanders, Belgium is expressed as a dimensionless K-value, calculated based on the mean U-value of the building envelope and the compactness of the building (compactness is the ratio of heated air volume to overall heat loss area). The results showed that the economically optimal insulation level lies at an insulation level K25–K30 (representing an overall U_{mean}-value = 0.35–0.40 W/m²K for the terraced

![Figure 5. Terraced house, usage period of 30 years, high energy price scenario, discount rate = 4%: the NPV over 30 years (NPV30) is given as a function of the total global warming potential. All results are presented in gray, whereas the trade-off curve is given in black. The solid black dots have a NPV30 > 0.](http://jen.sagepub.com)
house), thus far beneath the Flemish legal insulation requirement K45 (representing an overall $U_{\text{mean}}$-value = 0.61 W/m$^2$K for the terraced house). This economically optimal insulation level can be realized with ca. 15–20 cm roof insulation, 30 cm on the floor of the unheated attic, 15 cm in the façade, 10 cm in the ground floors and windows with $U_{\text{glass}} = 1.1$ W/m$^2$K and $U_{\text{frames}} = 1.8$ W/m$^2$K. However, not only the insulation level, but also the air tightness has a large impact (Figure 3: point A: $U = 0.36$ W/m$^2$K and no attention to air tightness versus point B: $U = 0.34$ W/m$^2$K and air tightness $n_{50} = 1/h$).

2. Second, selecting a well performing heating system, at least a high efficiency boiler or condensing boiler. If the budget is available, an air-to-water heat pump is a good alternative. It has a better energy performance, but also requires a higher investment.

3. Finally, if for any reason, further steps to decrease the energy consumption are wanted or needed, there are the options for limiting the ventilation losses through a balanced ventilation system with heat recovery, applying a ground-to-water heat pump and/or installing a solar driven system (thermal solar collector or PV-system). However, although these measures improve the energy performance, they are far beyond the economic optimum and beyond economic viability.

**DISCUSSIONS**

**Strengths and Weaknesses of the Optimization Methodology**

The multi-objective optimization program proved to be very useful in the search for optimized (extremely) low energy dwellings. For a good balance between computational time and approximation of the ideal Pareto front or trade-off curve, the population size was set at 100 chromosomes and the number of generations at 60. This resulted in a wide spread of Pareto optima. However, starting from these results, an in-depth analysis and fine tuning still was necessary in order to end up with all realistic building concepts. Therefore some adaptations and extra calculations needed to be performed.

First, the $U$-values of all envelope components needed to be analyzed. Despite the boundary condition for the overall insulation level, this constraint is not a guarantee that the $U$-value per envelope component does not exceed the maximum value set in the EPB standard as presented in Table 5. If the $U$-value was too high, the insulation thickness was increased in order to fulfil the requirement.
Second, the homogeneity of the insulation level of the building envelope needed to be analyzed. As the optimization process does not compare the insulation thicknesses of the different envelope components, some results might have very inhomogeneous distribution of the insulation, i.e., 2 cm roof insulation combined with 20 cm façade insulation or windows that combine a $U_{\text{glass}}$ of 0.7 W/m²K with a $U_{\text{frame}}$ of 3.6 W/m²K. These variants needed to be adapted to more homogeneous combinations and recalculated.

Both the maximum U-value and the homogeneity could have been incorporated theoretically as extra constraints in the optimization process. However, this would have increased the complexity of the penalty functions significantly and therefore the above control procedure has been selected.

In addition, some extra variants could be constructed by implementing the maximum insulation thickness for each envelope component and the best performing window characteristics on the optimal variants that resulted from the optimization process, if these variants were not yet present in the trade-off curve.

Finally, for those variants that violated the boundary condition for summer comfort, extra measures such as outer sun shading and/or night ventilation could be included, if not yet present, and a new evaluation of the summer comfort could be performed.

After this procedure of control and extension of the draft Pareto front, new simulations needed to be performed for all adapted variants and these results formed the basis to determine the final Pareto front or trade-off curve. This way, the evolutionary multi-objective optimization process is a useful tool for the development of (extremely) low energy dwellings, but final control of the results is indispensable to avoid the presence of unrealistic building concepts within the final optimal solutions.

### Table 6. Maximum U-value per envelope component according to the Flemish EPB (EPB, 2005).

<table>
<thead>
<tr>
<th>Building component</th>
<th>Maximum U-value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Façade</td>
<td>0.6</td>
</tr>
<tr>
<td>Roof</td>
<td>0.4</td>
</tr>
<tr>
<td>Window</td>
<td></td>
</tr>
<tr>
<td>Overall value</td>
<td>2.5</td>
</tr>
<tr>
<td>Glass</td>
<td>1.6</td>
</tr>
<tr>
<td>Floor above cellars</td>
<td>0.4</td>
</tr>
<tr>
<td>Floor slab on the ground</td>
<td>0.4</td>
</tr>
<tr>
<td>Wall/floor between flats</td>
<td>1.0</td>
</tr>
<tr>
<td>Common wall</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Embodied Energy versus Energy Savings (EPBT)

Figure 6 presents the energy payback time (EPBT) for energy saving measures on the building envelope and the installations of the terraced house. The EPBT is defined as the proportion of the extra embodied energy for energy saving measures to the yearly energy savings they achieve. Only the optimal solutions are shown. They are all derived (in 1 optimization run) for a usage period of 30 years, low energy price scenario, and a discount rate of 4%. By way of comparison, also the lines for an EPBT of 1 year and of 2 years are shown. These results show that the embodied energy of the energy saving measures should not be a reason of great concern, regardless of the applied insulation materials or installation systems. Even for extremely low energy dwellings (yearly energy savings >100 GJ compared to the non-insulated reference), the energy payback time remains <2 years. When comparing the extra embodied energy with the energy savings they realize, it is clear that in most cases the extra embodied energy (between 50 and 150 GJ for the terraced house) represents <10% of the primary energy savings over 30 years (30 × (30–110) GJ = 900–3300 GJ for the terraced house).

![Figure 6. Terraced house, usage period of 30 years, low energy price scenario: the extra embodied energy for energy saving measures on both the building envelope and installations is given as a function of the yearly primary energy savings. Only the results of the trade-off curve for NPV and total primary energy consumption are given. By way of comparison, also the lines for EPBT of 1 year and of 2 years are shown.](http://jen.sagepub.com)
Construction Costs versus Installation Costs

Analysis of the total present value (TPV) of all energy saving combinations (optimal and non-optimal) shows that first the TPV decreases with decreasing total primary energy consumption up to a minimum and then increases with further decreasing total primary energy consumption. The TPV mainly consists of the initial investment costs, the discounted replacement costs, and the discounted energy cost.

To analyze the impact of the different cost components on the evolution of the TPV, Figure 7 presents the TPV (open gray squares), the discounted constructional cost (dark gray squares), the discounted installation cost (light gray squares), and the discounted energy cost for all calculated energy saving combinations (optimal and non-optimal) for the low (black triangles) and high (gray crosses) energy scenario. The costs for the envelope in Figure 7 represent the initial investment and discounted replacement costs for the construction and the building envelope, where the costs for the installation represent the initial investment and discounted replacement costs for the installation. The energy price scenario has only an impact on the discounted energy costs. All results are valid for a usage period of

![Figure 7. Terraced house, usage period of 30 years, discount rate of 4%: partitioning of TPV (gray open diamonds) in discounted construction costs (dark gray solid diamonds), discounted installation costs (light gray solid squares), and discounted energy costs for the low (gray crosses) and high (gray open triangles) energy price scenarios of Table 3.](image-url)
30 years and a discount rate of 4%. The figure clearly shows the large contribution of the constructional cost to the TPV. The discounted constructional cost starts at 133,000€ for the non-insulated version and increases up to nearly 220,000€ for the most energy saving variants. In Figure 7, levels of constant constructional cost can be observed. This is caused by the fact that the first optimization step results in a certain number of optimized concepts for the building envelope. Only to these concepts, all kinds of installation types are applied in the second optimization step. Obviously, the total primary energy consumption of a building does not only depend on the building envelope, but also on the installation type that is added. This explains why the same cost for structure and envelope can be observed at different levels of primary energy consumption. The discounted installation cost starts at 26,000€ for the non-insulated reference situation and almost doubles when evolving to the most energy saving variants. However, the contribution to the TPV is much smaller than for the constructional cost and furthermore, for energy consumption levels in between, even lower costs than 26,000€ are possible. Obviously, the discounted energy cost decreases with decreasing energy consumption, but this cost is very small compared to the costs for the whole building. This results in very small differences in energy cost between the different energy price scenarios for extremely low energy houses.

![Initial extra cost for envelope and installation](image)

**Figure 8.** Terraced house, usage period of 30 years: initial extra cost for energy saving measures as a function of the yearly energy cost. The yearly energy cost of the reference situation is ca. 1600€.
Figure 7 presents the overall cost for the building, whereas a large part of the building cost consists of a fixed cost for the building structure, mostly independent of the insulation level. To analyze the impact of the energy saving measures only, Figure 8 presents the extra initial investment cost for the building envelope and the installation, compared to the non-insulated version of the terraced house as a function of the yearly energy cost. In the non-insulated situation, the terraced house has a yearly primary energy consumption of ca. 114,000 MJ, corresponding to a yearly energy cost of ca. 1600€. A decrease of the yearly energy cost with 50% can be realized with a total extra initial investment cost of ca. 8000–9000€, by combining energy saving measures on the building envelope for an extra cost of ca. 12,000€, with a well-performing, but smaller and thus, cheaper heating system (300–4000€ less than the reference case). By way of comparison are Points A–E (economically viable optimal solutions) from Figure 3 marked in Figure 8. As the figure shows, further decrease of the yearly energy cost is possible, but finally leads to an exponential increase of the extra initial investment cost. An annual energy cost of <300€ requires for the terraced house at least an extra initial investment cost of 60,000€ for the energy saving measures in the building envelope and 20,000€ for the installation, compared to the non-insulated version. This very high extra investment cost can be considered as one of the main barriers for the realization of extremely low energy dwellings.

Impact of Price Evolutions and Energy Prices

Analysis of the energy price scenarios showed that almost the same optimal combinations are found for all three scenarios. The only difference is that some solutions that are not economically viable for low energy prices, become viable when the energy price significantly increases. The hierarchy of energy saving measures as presented above however does not depend on the scenario.

Similar results were found from the analysis of the discount rate. Most results were calculated for a discount rate of 4%, but as the real discount rate is uncertain, different scenarios have been analyzed: a discount rate of 2, 4, and 8%. The larger the discount rate, the less importance is given to expenses in the distant future. For variants with average insulation level, the energy cost still has a significant impact on the NPV, meanwhile for extremely low energy houses, the initial investment cost dominates the NPV. This is reflected in Figure 9 by the fact that for variants with total primary energy consumption higher than 1000 GJ there is a shift in NPV for the different discount rates. The higher the discount rate, the less variants are economically viable and the flatter the curve of optima in the range of
higher energy consumption. These phenomena are intensified in case of combination of high energy prices and high discount rates. For extremely low energy houses the discount rate has a much lower impact, as can be seen in Figure 9. The hierarchy of energy saving measures however remains identical, independent of the discount rate.

All presented results are calculated for a material cost evolution of 0% (only increase of material costs due to inflation). Since higher price evolutions are possible due to changing economical situations, different scenarios were analyzed for price evolution for (re)investment costs of 0, 2, and 4%. As could be expected the results showed that higher material cost will have the largest impact on extremely low energy houses, as here the investment costs are highest. However, the impact appeared to be much smaller than the impact of the energy price evolution or the discount rate. And once again, the scenarios had no impact on the hierarchy of energy saving measures.

**CONCLUSIONS**

A global methodology has been developed to optimize extremely low energy buildings from the point of view of energy use, costs, and environmental impact. A large number of energy saving measures, both on the building envelope and on the heating installations has been taken into account. The focus of the analysis here presented was laid on the determination of the trade-off between energy use and costs over an usage period.

**Figure 9. Terraced house, usage period of 30 years, low energy scenario: optimal solutions per discount rate scenario (a = 2, a = 4, and a = 8%).**
period of 30 years. First, the results of this extensive research project reaffirmed the economic optimum and the hierarchy of energy saving measures that was already found in less extensive earlier work. Analysis of price evolutions also showed that the economic optimum is not only independent of these cost scenarios, it also remains economically viable for all analyzed cases. Also the hierarchy of energy saving measures appeared to be independent of these scenarios. Obviously, the economic viability of some measures, such as the application of heat pumps or mechanical ventilation with heat recovery, will depend on the cost scenarios, but in contrast to what is sometimes assumed, none of the scenarios causes a shift in the hierarchy of energy saving measures.

Also concepts for extremely low energy dwellings have been determined, but none of them appeared to be economically viable for the current energy prices or discount rates. Only in case of much higher energy prices, some of these concepts will become cost-effective over 30 years. However, the largest barrier of all these concepts is the extremely high investment cost. Without financial support or incentives, these concepts will be limited to a small number of consumers with a high environmental consciousness that are willing to invest such a large budget in an extremely energy saving house.

Finally, in contrast to what is sometimes commonly assumed, there is no reason for great concern about the embodied energy of the energy saving measures. The embodied energy strongly increases with increasing insulation level, but at the same time it leads to large energy savings during the usage phase of the building. Regardless of the applied insulation materials or installation systems, the energy payback time is extremely low for energy efficient dwellings and is mostly <2 years.

ACKNOWLEDGMENTS

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Passivhaus Institut, Darmstadt, Certificates Window frames (in German), Eurotec GmbH, Holzwarmlfenster serie 0.5; HEUSER Türen + Fenster-Metallbau GmbH, Super-Warmlfenster U 07 Serie H 3200-120 PU; Woschko Winlite GmbH, Woschko Winplus.


ANNEX

*Annex A. Plans and façades of the terraced reference house.*
Annex A. Continued.