MOVING TOWARDS A MORE SUSTAINABLE BELGIAN DWELLING STOCK: THE PASSIVE STANDARD AS THE NEXT STEP?

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ABSTRACT

To efficiently move towards a more sustainable dwelling stock in Belgium, priorities need to be defined. Accordingly, it should be questioned if the new policy measure requiring the passive standard for newly built residential buildings from 2020 onwards is justified. This paper emphasises on the energy related aspects of the results of a PhD research. In the research residential buildings in the Belgian context were optimised from a life cycle environmental impact and cost perspective. The results proved that not for all dwelling types and layouts the passive standard is the optimal variant. A well-considered design, orientation and choice of dwelling type will be necessary to make the future requirement of the passive standard technically feasible and efficient.

KEYWORDS

integrated approach, life cycle assessment (LCA), life cycle costing (LCC), Pareto optimisation, passive houses, residential buildings

1. INTRODUCTION

Despite the political efforts during the past decennia to move towards more energy efficient buildings in Flanders (Belgium) no major results have been achieved (Hens 2007). Several reasons were identified for this failure. An important one is the fact that the investment cost is the major decision criterion of the builder, and not the (energy) costs-in-use. This was confirmed by Kaenzig and Wüstenhagen (2009). Other factors are the relatively long life span of buildings which results in a large existing stock that changes slowly; and the continuous expansion of the building stock with large detached houses being very popular. Moreover, the latter are often located at isolated places, inducing a lot of transport of the inhabitants. (Hens 2007; Allacker 2010) One important recent policy measure is the energy performance of buildings (EPB) which are gradually becoming severer (a.a. 2005a). The next step, forced by Europe, is the obligation of the passive standard for newly built dwellings from 2020 onwards (EU 2010; VEA 2010a). The question rises if this is the most efficient measure to be

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taken in the Belgian context. This was also questioned by Hernandez and Kenny (2011) for the Irish context, focussing on the energy aspect (embodied energy versus energy-in-use) and by Audenaert et al. (2008) focussing on the economic aspect.

Priorities to move towards a more sustainable Belgian dwelling stock were searched for as part of a PhD research (Allacker 2010) within the SuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling types) project (Allacker et al. 2011). This four-year project focused on residential buildings because of their high energy consumption and their large share (82% at the start of 2008) in the building stock (Belgian Federal Government 2009). The study was based on an integrated assessment of the environmental impact, financial cost and performance of representative dwellings. The aim was moreover to gain insight in the optimisation potential for existing and newly built dwellings. This paper focuses on some of the findings emphasising on the energy related aspects in view of the upcoming new legislation. The analysis of one case study is elaborated in detail to provide an in-depth understanding of the approach followed. However, more general findings are reported based on the results of all analysed case studies.

2. BACKGROUND

During the past decennia several studies investigated the efficiency of energy saving measures for residential buildings in Belgium (Verbeeck 2007; De Coninck and Verbeeck 2005). In the study of Dooms et al. (2008) the identified CO_2 emission reduction measures for residential buildings were linked to scenarios which provided insight in the impact of the measures considering the overall Belgian housing stock. The analysis of passive houses in Belgium was the focus of several other studies, combining energy simulations with in situ measurements (De Meulenaer et al. 2005; Manioglu et al. 2007). The energy saving potential of passive houses was moreover investigated in several European countries, amongst others Belgium (Joosten et al. 2006). All mentioned studies were however limited to the evaluation of energy consumption, costs and/or CO_2 reductions. The overall environmental impact of the energy saving measures was not considered, neither were costs and environmental impact assessed in an integrated way. Such studies were however carried out in other countries such as for instance the study made by Zimmermann et al. (2005). The research discussed in this paper investigated the overall life cycle environmental impact and cost of dwellings in the Belgian context and identified the actions in order of priority to reduce the impact and cost. The aim was to rank the measures according to their efficiency and to identify the most preferred insulation level, material choice, etc. within a certain budget for several representative dwellings.

3. METHODOLOGY

3.1 Approach

To identify the actions in order of priority to move towards a more sustainable dwelling stock, an integrated assessment of the life cycle environmental impact and cost was carried out for sixteen representative dwellings. Both existing and newly built dwellings were analysed in order to differentiate in recommendations and compare the optimisation potential of both. The environmental impact was estimated based on a life cycle assessment (LCA), while a life cycle costing (LCC) analysis was used for the cost aspect. The investment cost was also considered in terms of affordability. The priority of the actions was determined based on a ranking of the highest reduction in life cycle impact for the smallest increase in initial impact. In addition, priorities from a financial point of view were also determined to investigate if these coincided with the ones based on environmental impact.

3.2 Selection of Representative Residential Buildings

The Belgian dwelling stock is heterogeneous due to the dominance of the private investors on the housing market. It was therefore impossible to represent the whole stock through a limited number of case studies. Nevertheless, 16 dwellings were selected differing in construction period and typology. Despite the specificity of these cases, it is assumed that the findings are valid for similar dwellings and therefore cover a large range of the Belgian dwelling stock.

The selection was based on a national statistical socio-economic survey conducted in 2001 (NIS 2001). Four dwelling types were distinguished: a detached house, a semi-detached house, a terraced house and an apartment; differentiating between four construction periods: before 1945, 1945–1970, 1971–1990 and 1991–2001. The distribution of these in the current dwelling stock is shown in **FIGURE 1**. A selection of the case studies is presented in **FIGURE 2**, illustrating their divergence.

For each of the 16 dwellings both the existing variant and a newly built identical type were analysed. The existing variant was built according to common practice in the period of construction while the newly built variant was built according to common practice to date. Only future impacts and costs were considered. For the existing variant the analysis was thus limited to the use phase and the end-of-life (EOL) phase, while for the newly built variant the whole life cycle was taken into account.

The optimisation was limited to the newly built dwellings, however refurbishment of the existing dwellings is the focus of further analysis but has not been finalised yet. For the optimisation, several measures were investigated such as the insulation level, the air-tightness, the material choice and the heating services (including the production of domestic hot water and ventilation). Only currently available materials and techniques were considered, thus limiting the analysis to current technology. This paper focuses on the analysis of one of the detached dwellings, more specifically the type constructed in 1991–2001 (upper left picture in **FIGURE 2**), because it represents the building geometry of many currently built single family dwellings. The findings are however broadened based on the results of all cases.

FIGURE 1. Distribution of the four dwelling types for the considered construction periods (total equals 100%), based on NIS (2001).

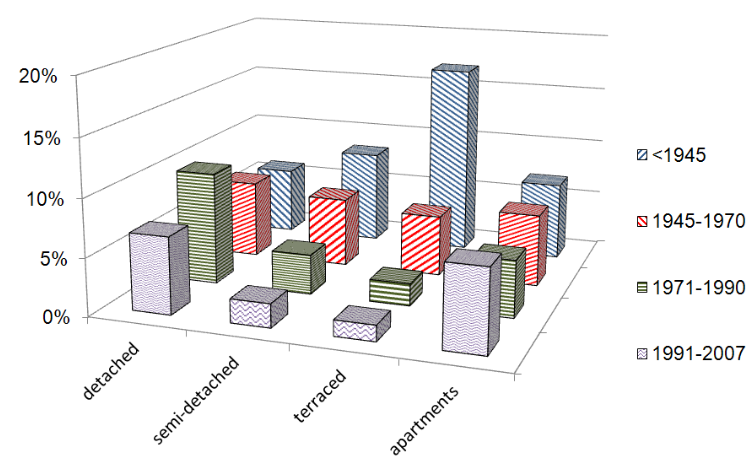


FIGURE 2. A selection out of the 16 analysed representative residential buildings, based on Allacker (2010, p. 161).

3.3 Integrated Assessment

All dwellings were assessed in a similar way. In a first step, the specific dwelling was simplified to improve its representativeness and all technical characteristics were gathered. In a second step the life cycle environmental impact and cost were assessed. For the analysis, a dwelling life span of 60 years was assumed. The environmental impact was expressed in monetary values, referred to as external costs (European Commission 2008). In a third step the actions in order of priority were identified by searching for the Pareto optima, both from an environmental and financial perspective. In a final step the Pareto optima were analysed in detail and compared to common practice to date and the dwelling as built originally. This approach is elaborated in detail for the detached dwelling, 1991–2001 in the subsequent paragraphs.

3.3.1 Analysis of the Dwelling Characteristics

The detached dwelling emphasised on in this paper was characterised by a total floor area of 123 m², a protected (heated) volume (V) of 382 m³, a building skin surrounding the heated volume (A_T) of 324 m² and a thermal compactness (C) of 1.18 m (V/A_T). The garage was assumed to be located in the heated volume in order to improve flexibility of the design by altering the garage to another function later. The dwelling consists of a ground floor and a first level covered by a pitched roof. The dwelling has 3 bedrooms and therefore was assumed to inhabit a two-parent family with two children.

The amount of elements (e.g. floor on grade, outer walls, inner walls and roof) was determined and the ratios (amount per m² floor area) were calculated. For each of the elements a reference for the construction period 1991–2001 and for newly-built dwellings was defined. For the newly built reference a solid and skeleton variant were distinguished. The element quantities, the corresponding ratios and the assumed reference U-values of the building skin elements are summarised in **TABLE 1**.

For the outer walls, for example, the reference built in 1991–2001 was assumed a cavity wall consisting of a primary layer of building clay bricks, gypsum plaster with acrylic paint as internal finishing, 4 cm rock wool and an air cavity of 3 cm, and a brick veneer as outer leave.

FIGURE 3. Architectural plans of the detached dwelling, 1991–2001 (Allacker 2010, p. 168).

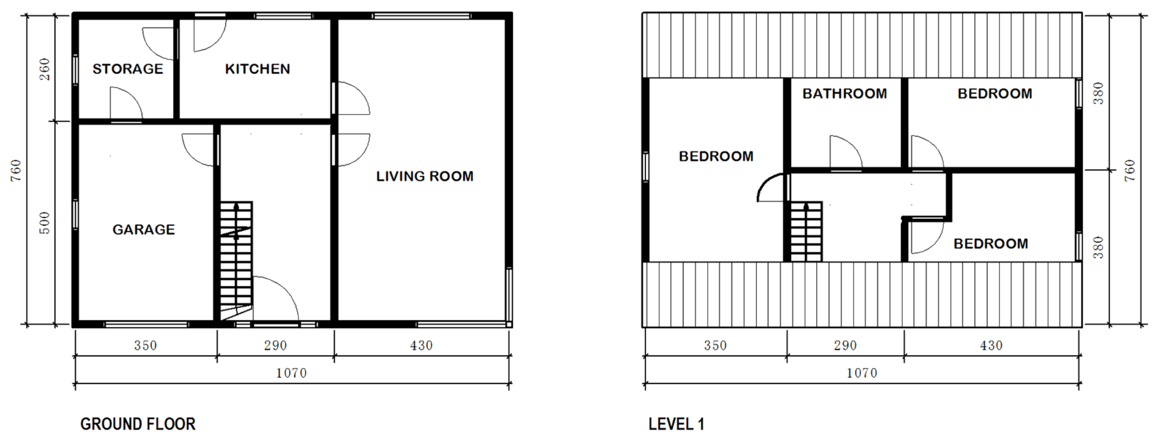


TABLE 1. Summary of the element quantities, their corresponding ratios and the assumed U-values (W/m²K) for the reference cases, partially based on Allacker (2010, p. 168).

				U-value (W/m²K)	
Element	**Amount**	**Unit**	**Ratio**	**1991–2001**	**Newly-Built**
Floor on Grade	81	m²	0.660	0.80	0.38
Foundation	37	m	0.297		
Outer Wall	103	m²	0.842	0.53	0.35a
Load-Bearing Inner Wall	53	m²	0.428		
Non-Bearing Inner Wall	86	m²	0.697		
Floor	78	m²	0.631		
Stairs	1	p	0.008		
Pitched Roof	81	m²	0.660	0.39	0.26
Windows Front Façade	7	m²	0.073	1.8/1.1[a]	1.8/1.1[b]
Windows Right Façade	5	m²	0.039		
Windows Back Façade	9	m²	0.070		
Windows Left Façade	2	m²	0.013		
Exterior Doors	1	p	0.016	1.61	1.61
Garage Door	1	p	0.008	0.52	0.52
Interior Doors	9	p	0.073		
Services	1	building	0.008		

[a]The outer walls for the skeleton reference were characterised by a U-value of 0.32 W/m²K .
[b]U_{frame} / U_{glass}

The newly built solid reference was assumed identical to the one for the period 1991–2001 but consisted of 7.5 cm rock wool instead of 4 cm. The newly-built skeleton reference was composed of a timber frame filled with rock wool (14 cm), a gypsum board and acrylic paint as internal finishing, an oriented strand board (18 mm) at the cavity side of the skeleton, a PE water-tight sheet, a 3 cm air cavity and a brick veneer as outer leave.

For the optimisation of the newly-built dwelling 13,440 variants were analysed, differing in floor insulation level (4 alternatives), outer wall insulation and external finishing (both for solid (6 alternatives) and skeleton (9 alternatives) variants), pitched roof structure and insulation level (14 alternatives), window frame and glazing (4 alternatives) and heating services (4 alternatives). Analysing all possible combinations of these alternatives resulted in 5,376 solid variants (4x6x14x4x4) and 8,064 skeleton alternatives (4x9x14x4x4). The alternatives of the different building elements are listed in **TABLE 2**.

TABLE 2. Overview of the analysed variants of the different building elements based on Allacker (2010, p. 264).

	Solid	Skeleton
Foundation	FOUND1: in situ concrete	
Floor on Grade	GRFL0: concrete slab—no insulation—ceramic tiles GRFL1: concrete slab—3 cm PUR foam—ceramic tiles GRFL2: concrete slab—10 cm PUR foam—ceramic tiles GRFL3: concrete slab—21 cm PUR foam—ceramic tiles	
Outer Wall	OW0: building bricks—no insulation—brick veneer OW1: building bricks—7,5 cm rockwool—brick veneer OW2: building bricks—14 cm rockwool—brick veneer OW3: building bricks—20 cm rockwool—brick veneer OW8: building bricks—14 cm EPS—stucco OW9: building bricks—20 cm EPS—stucco	OW10: timber frame + 14 cm cellulose—brick veneer OW17: FJI + 24 cm cellulose—larch OW18: FJI + 30 cm cellulose—larch OW19: FJI + 36 cm cellulose—larch OW20: FJI + 41 cm cellulose—larch OW17b: FJI + 24 cm cellulose—brick veneer OW18b: FJI + 30 cm cellulose—brick veneer OW19b: FJI + 36 cm cellulose—brick veneer OW20b: FJI + 41 cm cellulose—brick veneer
Pitched Roof	PR0: rafters + purlins—no-insul PR1: rafters + purlins—8 cm rock wool PR3: rafters + purlins—22 cm rock wool PR4: rafters + purlins—26 cm rock wool PR5: rafters + purlins—30 cm rock wool PR7: rafters + purlins—38 cm rock wool PR0b: rafters—no insulation PR9: rafters—10 cm rock wool PR10: rafters—14 cm rock wool PR11: rafters—18 cm rock wool PR12: rafters—20 cm rock wool PR13: rafters—24 cm rock wool PR14: rafters—28 cm rock wool PR15: rafters—30 cm rock wool	
Loadbearing Inner Wall	LIW1: bricks—gypsum plaster	LIW4: timber frame + rock wool—gypsum board
Non-Bearing Inner Wall	NLIW3: metal stud + cellulose—gypsum board	
Floor	FL1: hollow concrete slab—carpet	FL2: wood beams—carpet
Window	W1: meranti frame (standard) + standard double glazing + aluminum glass profile W2: meranti frame (standard) + thermally improved glazing + aluminum glass profile W3: meranti frame (insulated) + thermally improved glazing + thermally improved glass profile W4: meranti frame (insulated) + triple glazing + thermally improved glass profile	
Services	SERV1: condensing gas boiler + low temperature panel radiators + coupled instant hot water production + ventilation C SERV2: condensing gas boiler + low temperature panel radiators + solar boiler (domestic hot water) + ventilation C SERV3: ground/water heat pump + low temperature panel radiators + solar boiler (domestic hot water) + ventilation C SERV4: pellet boiler + low temperature panel radiators + solar boiler (domestic hot water) + ventilation C	
Number of Variants	**5,376**	**8,064**

3.3.2 Environmental Impact

The environmental impact was evaluated through a life cycle assessment (LCA), defined by the ISO 14040 standard as *'the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle'* (ISO 14040 2006, p. 2). To enable a full assessment as many impacts as possible were considered, more specifically all impacts of the Eco-Indicator 99 method (Goedkoop and Spriensma 2001) were included. An endpoint approach was chosen for its greater relevance for decision support compared to a midpoint approach (Bare et al. 2000). An endpoint approach moreover enables to calculate a single score for all assessed impacts which allows straightforward decisions in case of contradictory indicators. It was decided to express the environmental impacts in monetary values to improve comprehensibility. This should improve communication and therefore enable to reach the broad number of stakeholders in the building sector.

The monetary values of the environmental impacts were referred to as external costs (European Commission 2008; Mizsey et al. 2009), and were defined based on a combination of existing methods in order to cover as many impacts as possible. The values were mainly determined on the willingness-to-pay approach and thus express how much people are prepared to pay to avoid the impacts. The European ExternE method was used for the assessment of the human health impact and impact on crops of five key airborne emissions (European Commission 2008, Friedrich 2011). More specifically, were the values of the CAFE project used which were estimated for the Belgian context (mid estimate) (Holland et al. 2005, p. 13–17). The monetary values of the combination of methods are summarised in **TABLE 3**, based on (Holland et al. 2005; Davidson et al. 2002–2005; European Commission 2008; Torfs et al. 2005; Ott et al. 2006; European Commission 2006; De Nocker et al., internal report, 2007[3]). A justification of the developed method, embedded in an extended discussion on external costs, was elaborated in Allacker (2010) and Allacker and De Nocker (2012). Similar to the weighting factors of other impact assessment methods aiming at a single score, the monetary values include a degree of uncertainty. This is reflected through the widely diverging ranges of monetary values found in literature (Huppes and Ishikawa, 2005). A comparison of four methods, implemented for construction related products and processes, however revealed that these led to identical decisions besides few exceptions (Allacker and De Nocker 2012). Transparent reporting and sensitivity analysis of the most uncertain values seem two important features.

The Ecoinvent version 2.0 database (ecoinvent 2009) was used for the inventory of the in- and outputs of the materials and processes. The data for the building materials were however adapted to improve their representativeness for the Belgian context by changing the Swiss electricity mix to the European mix. It was assumed that the building materials on the Belgian market were produced all over Europe. These adaptations were made by the Flemish Institute for Technological Research (VITO).

The transport and the end-of-life (EOL) treatment scenarios of the materials were based on a survey conducted by the Belgian Building Research Institute (BBRI) in 2008 amongst Belgian contractors, producers, dealers, waste sorting and treatment companies. The life span of the different building elements and materials, together with the necessary cleaning,

[3]De Nocker L., Bronders J., Liekens I., Patyn J., Smolders R. and Engelen G. (2007). "Uit- en doorwerking van langetermijndoelstellingen in het milieu- en natuurbeleid, Finaal rapport Case Grondwater." Flemish Institute for Technological research (VITO), Mol, Belgium.

TABLE 3. Summary of the monetary values of the considered emissions and impacts, based on Allacker (2010, p. 69).

Emission/Impact	External Cost	Unit	Source
Airborne emissions, impacts on human health and crops			
$PM_{2.5}$	61,000	€/ton	ExternE - CAFE (Holland et al. 2005, p. 13–17, mid estimate, data for Belgium)
SO_2	11,000	€/ton	
NO_x	5,200	€/ton	
NH_3	30,000	€/ton	
VOC	2,500	€/ton	
Greenhouse gasses (calculated according to CML2000[a])			
CO_2 equivalents	50	€/ton equivalent	(Davidson et al. 2002; 2005)
Impacts calculated according to Eco-Indicator 99			
human health (except due to above emissions)	60,000	€/DALY[b]	(European Commission 2008; Torfs et al. 2005)
ecotoxicity	0.49	€/PDF[c]xm²xyear	(Ott et al. 2006)
depletion of resources	0.0065	€/MJ	(European Commission 2006)
freshwater	1.22	€/m³	(De Nocker et al. 2007)[3]

[a]CML = Centrum Milieukunde Leiden
[b]DALY = Disability Adjusted life years
[c]PDF = Potentially Disappeared Fraction

maintenance and replacements scenarios were based on a literature study. Several sources were consulted and combined, amongst others a.a. (1991), Perret (1995), BCIS (2006), Anderson and Howard (2000), IVAM (1995), Blom (2005) and Haas et al. (2006a,b, 2008).

The assessment of the energy consumption during use phase was limited to space heating, production of domestic hot water and ventilation. The electricity consumption due to appliances and lighting was not considered because it was assumed to be less determined by the building design. For the comparison of the dwelling alternatives, these were thus not of importance. The net heating demand was estimated by steady state energy calculations in line with the formulae defined in the Flemish decree on Energy Performance of Buildings (EPB) (a.a. 2005b). The end energy consumption was based on the calculated net energy demand and the efficiency of the complete heating system. No cooling was considered. The efficiency was determined according to the prescriptions of the Energy Performance Certificate (EPC) (Berben, 2008) because these were more precise than the EPB estimations, except for high efficiency and condensing boilers. The efficiency of the latter was calculated according to Van der Veken and Hens (2010) and were determined on a monthly base in function of the heat losses and heat gains; and the selected control mechanism.

For the production of domestic hot water the formulae of the Passive House Platform (PHPP) were used because these are based on the number of inhabitants (Feist et al. 2001), while the EPB estimates these in relation to the volume of the dwelling. The PHPP was found to correspond better to an average behaviour.

3.3.3 Financial Cost

Unaffordable measures or those which are not of interest from a life cycle perspective will most probably not be chosen by the average Belgian citizen—even though these might reduce the environmental impact. Therefore, the investment cost was considered in terms of affordability while the life cycle cost was analysed in terms of life time efficiency. The latter was calculated based on a life cycle cost analysis through the sum of the present values of all costs occurring during the life span of the dwelling (Flanagan et al. 1989, ISO 2006).

The construction costs were retrieved from the ASPEN database (ASPEN 2008a). This database is valid for the Belgian context and contains all building related costs (i.e. labour, material and indirect costs). The average prices for households in Belgium in 2008 (European Commission 2009) were used for the energy costs and the EOL costs were based on a survey conducted by the BBRI in 2009. The cleaning and maintenance costs were retrieved from literature (Pasman et al. 1/1993; Hollander den et al. 3/1993; Ten Hagen Stam 2000a,b; a.a. 2000; ASPEN 2008a,b; UPA-BUA 2009). The growth rates of material, labour and energy costs needed to be predicted to calculate the future costs during the life span of the dwelling. To calculate the present value, a discount rate was required as well. These economic parameters were estimated based on the analysis of the evolution of prices during the past 50 years (Dexia Bank 2007; De Troyer 2007; ABEX 2009) and of predictions for the coming years (Federaal Planbureau 2007; D'haeseleer 2007). The assumptions are summarised in **TABLE 4**. Sensitivity analyses of the economic parameters proved that the results were fairly robust (Allacker 2010), the results of these sensitivity analyses are therefore not elaborated in this paper.

3.3.4 Optimisation

Out of all 13,440 analysed variants of the dwelling, the one with the lowest initial cost was determined. Starting from this option the most efficient measures were identified to reduce the life cycle cost. These were defined as the measures with the highest reduction in life cycle cost for the lowest increase in initial cost. Both the financial and external costs were assessed. The resulting variants out of the whole population of options were defined as the Pareto optima and graphically presented by the Pareto front (cfr. **FIGURE 4**) (Marler and Arora 2004). Each solution on the Pareto front was analysed in detail. The financial consequences

TABLE 4. Economic parameters, based on Allacker (2010, p. 92).

Parameters (yearly real rates)	
discount rate	2%
growth rate of construction costs	0.5%
growth rate of energy prices	2%

[4]The K-value of a building refers to its level of global heat insulation value. It is obtained by multiplying the ratio of the average heat transmittance coefficient U_m (W/m²K) and a reference value ($U_{m,ref}$) by 100. The reference value depends on the compactness (C) of the building. For a compactness lower than or equal to 1 m, the $U_{m,ref}$ equals 1, for 1 < C < 4 m, $U_{m,ref}$ equals (C+2)/3 and for C ≥ 4 m, $U_{m,ref}$ equals 2 W/m²K. The U_m value was calculated according to the Belgian norms. (a.a. 2007, p. 57228–57229)

The E-value of a building is a measure of its yearly primary energy use compared to a reference, multiplied by 100 (a.a. 2005b). The reference value ($E_{char\ ann\ prim\ en\ cons,ref}$) equals 115 x $A_{T,E}$ + 70 x V_{EPW} + 105 x $V_{dedic,ref}$. $A_{T,E}$ is the enclosure (m²), V_{EPW} is the heated volume (m³) and $V_{dedic,ref}$ is the ventilation rate (m³/h). All are calculated according to the Flemish EPB (a.a. 2005b).

were investigated for the Pareto optima determined from an environmental point of view to check the affordability (both investment and life cycle cost). Because heating was proved to be an important contributor to the external cost, the K and E-values[4] (according to the Flemish regulations) of all options were calculated. This allowed gaining insight in the optimal values for each of the dwellings analysed.

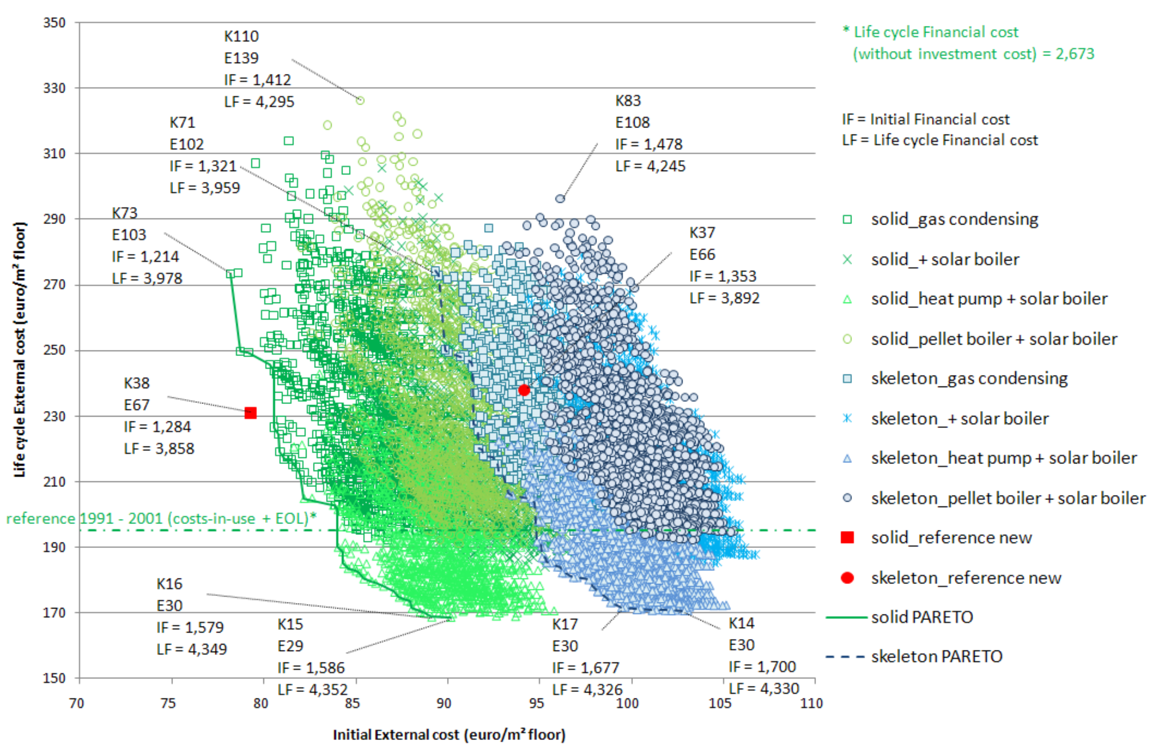
4. FINDINGS

4.1 Detached, 1991–2001

4.1.1 Environmental Assessment: External Costs

The initial and life cycle external cost, expressed per m² floor area, of all analysed variants were graphically presented, including the indication of the Pareto optima (**FIGURE 4**). Every dot on the graph represents one dwelling alternative. A distinction (different symbol) was made between the solid and skeleton variants and between the different heating systems. The K- and E-value and the financial consequences are indicated for the references (common practice to date), the options with the highest life cycle external cost and some of the Pareto optima. The analysis proved that although the initial external cost of the skeleton variants is higher, the life cycle cost is in the same order of magnitude as for the solid variants. Improving the insulation level of the building was identified as a first priority (first part of the Pareto front), followed by the choice for a more efficient heating service system (second part of the Pareto front). This is further elaborated in the subsequent paragraph.

FIGURE 4. Initial and life cycle external cost of the analysed variants of the detached dwelling, 1991–2001, based on Allacker (2010, p. 294).

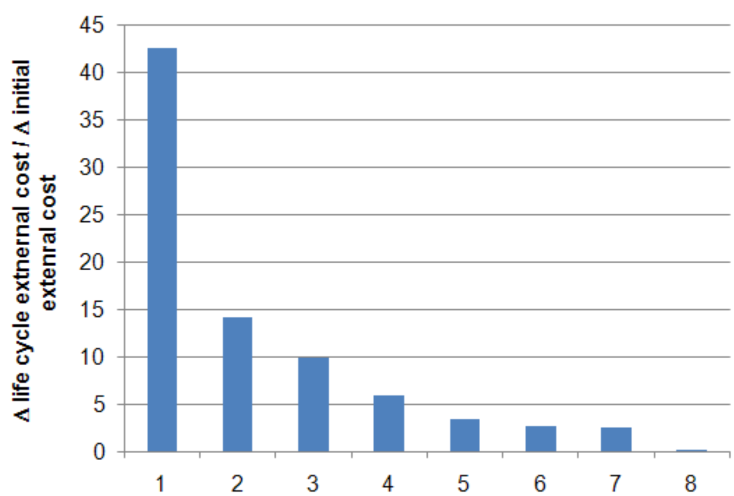


The decreasing marginal efficiency of the Pareto optima for a decreasing life cycle cost is presented in **FIGURE 5**. This marginal efficiency was defined as the ratio of the life cycle cost reduction and the initial cost increase. The Pareto optima in **FIGURE 5** are limited to the most efficient measures which are the optima situated on the concave outer border of the Pareto front. This overview illustrates that the last measure (case 8 in **FIGURE 5**: 38 cm rock wool in the pitched roof) can be questioned because the efficiency is nearly zero. The option with the second lowest life cycle external cost is measure 7 (**FIGURE 5**). This option consists of triple glazing, a floor on grade with 21 cm PUR foam, outer walls with an external finishing of stucco on 20 cm EPS insulation, a pitched roof with 30 cm rock wool and a heat pump for space heating (including a solar boiler for the production of domestic hot water). This dwelling is characterised by K16 and E30. The yearly net energy demand equals 51 kWh/m^2 floor. For this dwelling an air-tightness of 6 air changes per hour (ACH) was assumed.

FIGURE 5. Detached dwelling, 1991–2001: decreasing marginal efficiency of the Pareto optima based on the external cost (solid variants).

	windows	floor on grade (cm)	outer walls: stucco on (cm)	pitched roof (cm)	services
	VAR1[a]	—	EPS: 14	—	gas boiler
1	VAR1	—	EPS: 14	RW: 8	gas boiler
2	VAR2[b]	PUR: 10	EPS: 14	RW: 8	gas boiler
3	VAR2	PUR: 10	EPS: 14	RW: 8	heat pump
4	VAR3[c]	PUR: 10	EPS: 14	RW: 8	heat pump
5	VAR4[d]	PUR: 10	EPS: 14	RW: 30	heat pump
6	VAR4	PUR: 10	EPS: 20	RW: 30	heat pump
7	VAR4	PUR: 21	EPS: 20	RW: 30	heat pump
8	VAR4	PUR: 21	EPS: 20	RW: 38	heat pump

[a]standard timber frame + standard double glazing: Uframe = 1.8 W/m²K, Uglazing = 2.9 W/m²K, g = 0.75
[b]standard timber frame + thermally improved glazing: Uframe = 1.8 W/m²K, Uglazing = 1.1 W/m²K, g = 0.6
[c]insulated timber frame + thermally improved glazing: Uframe = 0.74 W/m²K, Uglazing = 1.1 W/m²K, g = 0.6
[d]insulated timber frame + triple glazing: Uframe = 0.74 W/m²K, Uglazing = 0.6 W/m²K, g = 0.6
*abbreviations: PUR = polyurethane, EPS = expanded polystyrene, RW = rock wool



If attention is paid during construction to the air-tightness, it can be lowered to 0.6 ACH per hour (passive standard). The yearly net energy demand for heating is then lowered to 35 kWh/m^2 floor. This is higher than the maximum allowed for the passive standard (15 kWh/m^2 (PHPP 2010)) and slightly higher than the low-energy variant (30 kWh/m^2 floor (VEA 2010b)). Measure 7 leads to a reduction in the life cycle external cost of 38% compared to the first Pareto optimum. However, it results in an increase of the financial investment and life cycle cost of respectively 30% and 9%. The question thus rises if building owners will be prepared to make this extra investment (if not obliged) or if external support (via policy measures) will be necessary.

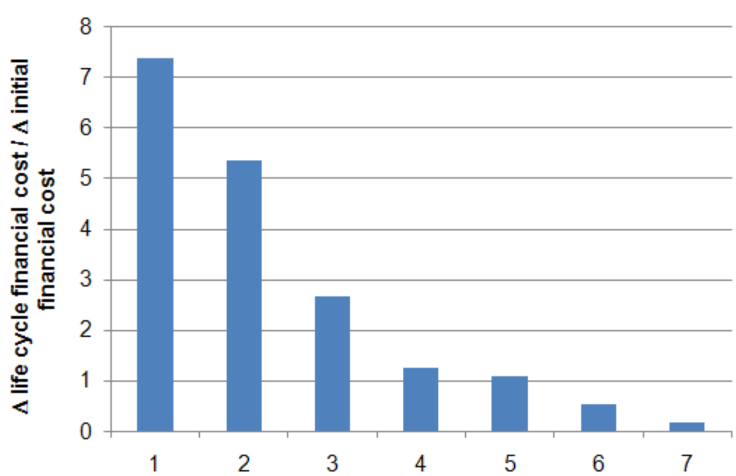
4.1.2 Economic Assessment: Investment and Life Cycle Costs

A similar analysis was made from a financial perspective. The most efficient Pareto optima are summarised in **FIGURE 6**. The marginal efficiency of the last two measures is low (<1) and these can therefore be questioned. The option with the lowest life cycle financial cost excluding the last two measures (measure 5 in **FIGURE 6**) is composed of thermally improved glazing, a floor on grade with 21 cm PUR, an outer wall with a brick veneer as outer leave and

FIGURE 6. Detached dwelling, 1991–2001: decreasing marginal efficiency of the Pareto optima based on the financial cost (solid variants).

	windows	floor on grade (cm)	outer walls: (cm)		pitched roof (cm)	services
	VAR1[a]	—	stucco	EPS: 14	-	
1	VAR2[b]	PUR: 10		EPS: 14	-	
2	VAR2	PUR: 21		EPS: 14	-	
3	VAR2	PUR: 21		EPS: 14	RW: 8	gas
4	VAR2	PUR: 21	brick veneer	RW: 14	RW: 8	boiler
5	VAR2	PUR: 21		RW: 14	RW: 14[c]	
6	VAR2	PUR: 21		RW: 20	RW: 18[c]	
7	VAR2	PUR: 21		RW: 20	RW: 30	

[a]standard timber frame + standard double glazing: Uframe = 1.8 W/m^2K, Uglazing = 2.9 W/m^2K, g = 0.75
[b]standard timber frame + thermally improved glazing: Uframe = 1.8 W/m^2K, Uglazing = 1.1 W/m^2K, g = 0.6
[c]roof structure: closely placed rafters instead of rafters and purlins
*abbreviations: PUR = polyurethane, EPS = expanded polystyrene, RW = rock wool



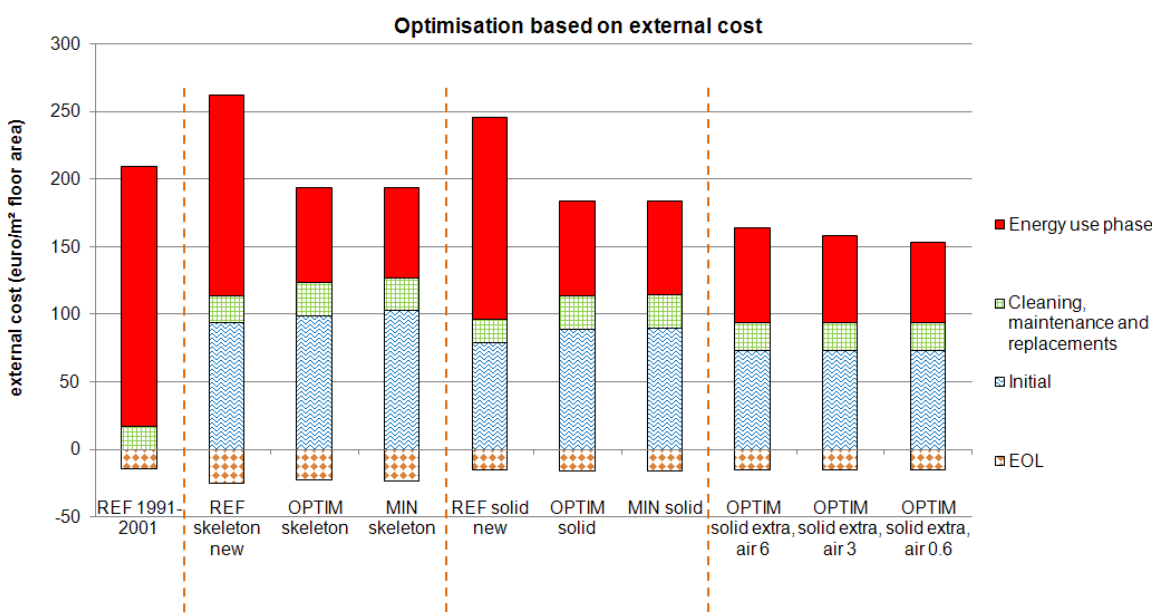
14 cm rock wool as cavity insulation, a pitched roof of closely placed rafters with 14 cm rock wool and a condensing gas boiler for space heating. This dwelling is characterised by K26 and E54, which is higher than option 7 according to the previous hypothesis (based on external costs). It corresponds with a yearly net heating demand of 62 kWh/m² floor. However, if again a better air-tightness of 0.6 ACH is assumed, the yearly net heating demand equals 46 kWh/m² floor. Measure 5 required an extra investment of 6.5% (79.42 euro/m² floor) compared to the first Pareto optimum and resulted in a reduction in life cycle cost of 5% (195.36 euro/m² floor). This measure moreover led to a 24% reduction in life cycle external cost.

The marginal efficiency of the measures based on financial cost was much lower than of these based on external cost (e.g. 7 compared to 43 for the most efficient measure). Because the priorities were completely different based on both criteria, decisions based on financial and external cost differ.

4.1.3 Importance of the Different Life Cycle Phases

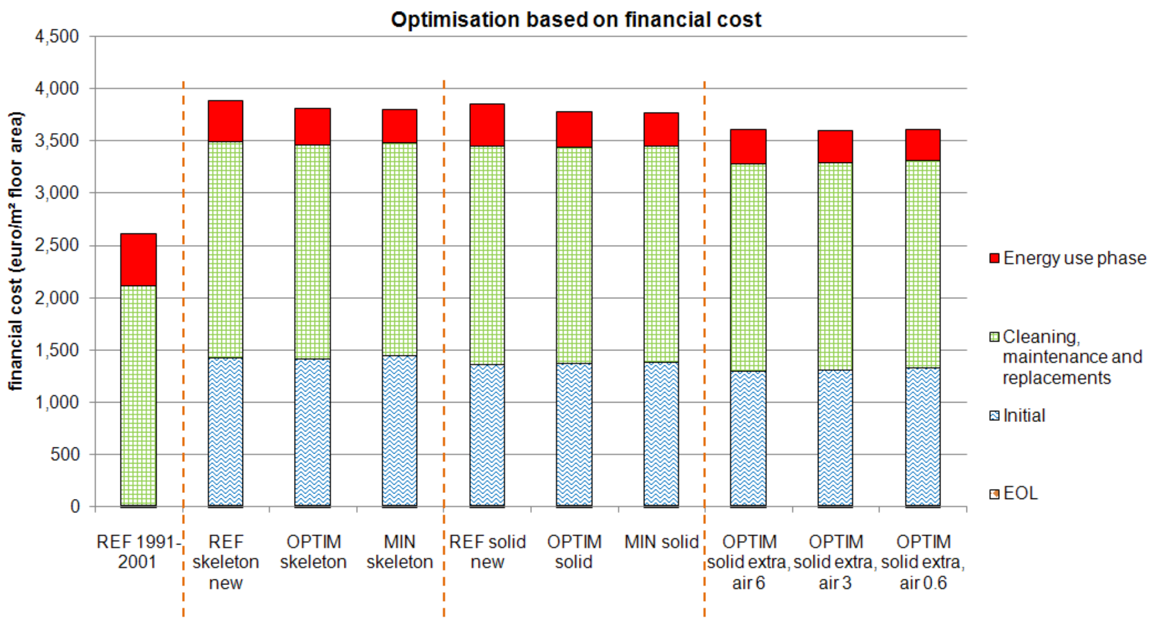
A detailed analysis of the contribution of the different life phases to the life cycle external (**FIGURE 7**) and financial (**FIGURE 8**) cost was made to clarify the identified ranking of the measures and to gain insight in priorities for further optimisation. **FIGURE 7** summarises the life cycle external costs of the reference dwellings, the most preferred options (as defined above and indicated in the graph by 'OPTIM'), the options leading to the lowest life cycle external cost of all analysed options (indicated in the graph by 'MIN') and some extra analysed variants (last three on the graph). The third last option represents a further optimisation of the 'OPTIM' solid variant, not differing in insulation level, but only in material choice.[5] The last

FIGURE 7. Detached dwelling, 1991–2001: Importance of the life phases from an environmental point of view for a selection of the analysed options.



[5]The extra optimum consists of a floor covering of laminate instead of ceramic tiles for the floor on grade; perforated clay bricks instead of building clay bricks for the structural layer of the outer walls; sand-lime bricks for the load-bearing inner walls; cellulose instead of rock wool for the pitched roof and a wood wool board instead of a cement fibre board for the sub-roof.

FIGURE 8. Detached dwelling, 1991–2001: Importance of the life phases from a financial point of view for a selection of the analysed options.



two options are identical to the previous one, but with an improved air-tightness (3 and 0.6 ACH respectively).

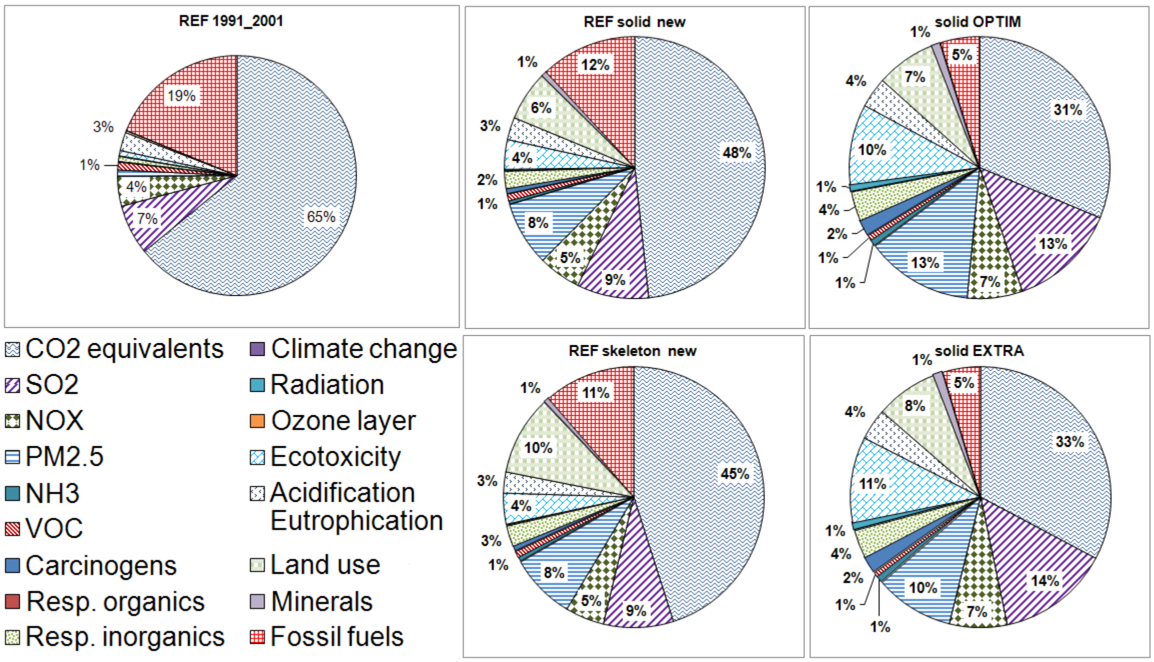
The graph clearly shows the importance of the energy consumption during use phase in the life cycle external cost. The first priority from an environmental point of view is therefore energy saving. For the optimised variants however, the initial phase represents the largest fraction of the life cycle costs. Although the EOL external costs were negative costs (and thus lead to positive effects) due to the recycled (or reused) part of the materials and/or due to energy recovery by incinerating some of the materials, these only represented a small part of the initial cost. It seems important to increase the percentage of recycling and reuse in future to further increase the positive effect. **FIGURE 8** is a similar graph but is based on an optimisation from a financial perspective and focuses on the financial costs.[6] In contrast to the external cost, the periodic costs for cleaning, maintenance and replacements represent the most important part of the life cycle cost. These are followed by the investment costs. The energy costs are relatively small compared to the other costs. This clarifies the difference in priorities between decisions based on external and financial costs.

4.1.4 Improvement of Each of the Different Impacts Considered

The above described optimisation of the external cost was based on the sum of the costs of all impacts. This section focuses on the contribution of each of the impacts to this overall cost and on the reduction/increase of the most important ones due to the measures taken. In **FIGURE 9** the contribution of the impacts to the life cycle external cost is shown for five dwelling variants:

[6]The third last extra optimum for the financial cost optimisation consists of a floor covering in carpet instead of ceramic tiles for the floor on grade (only living room); a concrete block veneer instead of brick veneer; concrete roof tiles instead of ceramic roof tiles and 18 cm cellulose flakes instead of 14 cm rock wool between the closely placed rafters of the roof structure. The last two extra optima are identical to the previous one but with an improved air-tightness of 3 and 0.6 ACH respectively.

FIGURE 9. Detached dwelling, 1991–2001: relative contribution of the impacts to the life cycle external cost.

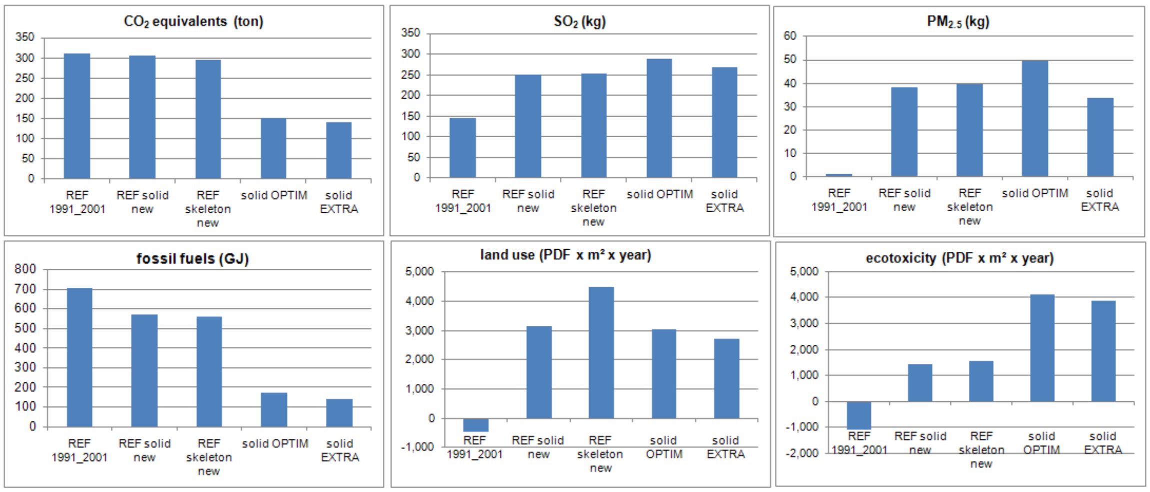


the reference 1991–2001, the solid and skeleton reference for newly built dwellings, the 'optim' solid variant (fifth last option of **FIGURE 7**) and the extra variant (the third last option of **FIGURE 7**). The graph for the reference 1991–2001 is based on the remaining life phases of the dwelling (excluding initial effects), while the other graphs represent the whole life cycle of the dwellings. The impacts due to the CO_2-equivalents were identified as most important for all variants, with a contribution varying from 65% for the existing dwelling to slightly less than 50% for common practice to date and about 30% for the optimised variants.

For the reference dwellings, the CO_2-equivalents were followed—in order of importance—by the depletion of fossil fuels (ranging from slightly less than 20% for the existing dwelling to about 10% for common practice to date), land use in case of the skeleton reference, and the impacts due to SO_2 and $PM_{2.5}$ emissions. The latter was however only of importance for the newly built variants (due to the production of materials). The optimal variants showed a reduced importance of the depletion of fossil fuels (heating with heat pump instead of condensing gas boiler), but an increased importance of SO_2 and $PM_{2.5}$ emissions, ecotoxicity and ionising radiation. The influence of the measures taken was investigated and is presented for the six most important emissions and impacts (**FIGURE 10**).

The CO_2-equivalents of the optima were halved compared to the reference dwellings and the consumption of fossil fuels was reduced to about one fourth. The SO_2 and $PM_{2.5}$ emissions increased by 20% and 25% respectively for the 'solid OPTIM' variant compared to common practice to date, but by choosing other building materials (solid EXTRA) could be reduced again, resulting in a slight increase (2%) of SO_2 emissions and in a decrease (18%) of the $PM_{2.5}$ emissions compared to common practice to date. The impact due to land use was identified as being most important for the skeleton variants due to the need of timber and timber based materials. The effect of the optimisation measures on land use was proved to be

FIGURE 10. Detached dwelling, 1991–2001: reduction or increase of the most important impacts.



small. Ecotoxicity was remarkably higher for the optimised variants compared to the reference dwellings. This was due to the production phase; and heating and domestic hot water production during use phase (changing from natural gas to electricity).

4.2 Extension of the Findings, Based on the Sixteen Representative Dwellings

The above results should be interpreted with care because these were based on a single case. In the subsequent paragraphs, the findings are therefore broadened based on the results of the analysis of the sixteen case studies.

4.2.1 Passive Standard as Optimum?

For the above described dwelling the most preferred (optimal) option (with the lowest life cycle cost for a relatively low increase in initial cost) was identified as a dwelling with a yearly net heating demand above the maximum allowed for passive buildings (15 kWh/m² floor) and low energy buildings (30 kWh/m² floor), both from an environmental and financial perspective. This was however not a general conclusion for all analysed cases. Based on the financial cost, the yearly net heating demand of the optimum of two of the sixteen cases was between 15 and 30 kWh/m² floor and one reached the passive standard. From an environmental perspective, the optimum of eight dwellings was characterised by a net heating demand between 15 and 30 kWh/m² floor and two below 15 kWh/m² floor. It is however important to remark that no analysis was made of dwellings specifically designed to fulfil the passive standard. For dwellings with amongst others an adapted design, layout and glazing, the passive standard may be the optimum. However, the results of the analysis pointed out that the foreseen passive standard for newly built dwellings will require an adaptation of current building practice and building layout prescriptions in order to make it technically feasible and efficient.

4.2.2 Priorities from an Environmental Perspective, Financially Affordable and Justifiable?

For ten of the sixteen dwellings the environmental optima resulted in a reduction in the life cycle financial cost. The life cycle financial cost was on average reduced by 1%, with a maximum of 16%. The majority of the measures were thus proved to be justifiable from a life cycle cost perspective. However, because some of the environmental optima resulted in an increase in life cycle financial cost, the measures should be carefully considered. An average increase in the financial investment cost was found of 6%. The environmental optima therefore seemed affordable; if not for the private dwelling owner, certainly through means of support from the government.

4.2.3 Priorities and Optima Identical from a Financial and Environmental Perspective?

The analysis revealed that for all dwellings the optima based on environmental and financial considerations differed. Not only did the optima differ, but also the order of priority of the measures to be taken. The optima from an environmental point of view resulted in a higher insulation level and lower yearly net heating demand than the ones from a financial perspective. Because the majority of the population is only interested in the financial benefits, incentives will be needed if the government wants to convince people to achieve the environmental optima. Another option is the internalisation of the external costs so that these influence the choices of the decision-makers. However, the investigation proved that this influence will be small—based on the assumed monetary values of the impacts—because the external cost represented only about 5 to 10% of the financial costs.

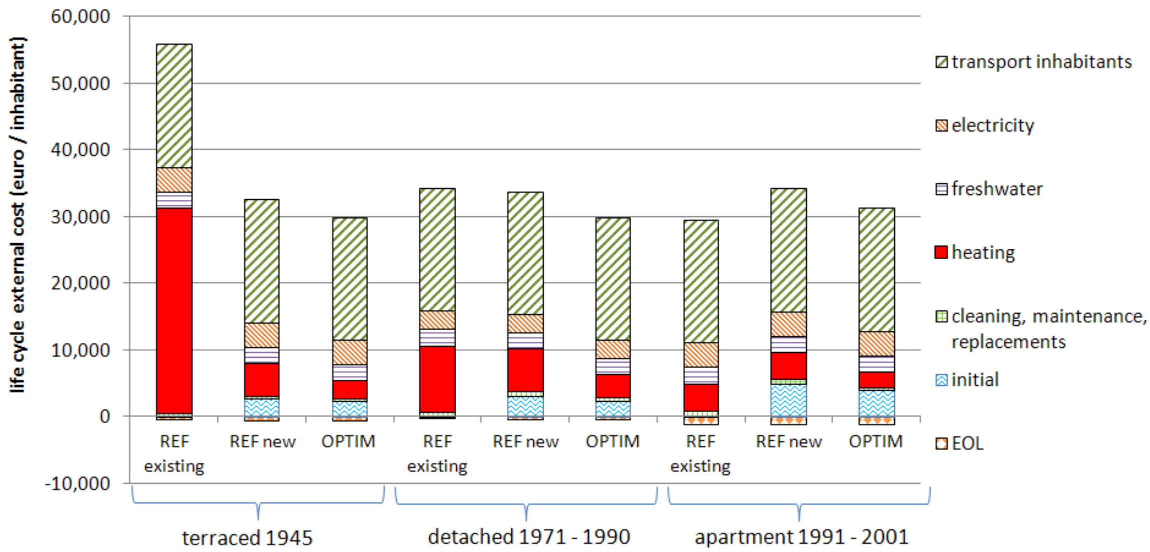
4.2.4 Importance of the Different Life Cycle Phases and Processes

The importance of the life phases, as elaborated in section 4.1.3 for the detached dwelling, was similar for all case studies. In order to gain insight in the importance of the not yet considered processes during use phase, more specifically electricity use for appliances and artificial lighting, freshwater consumption and transport of the inhabitants, these were roughly estimated (based on average data[7]) and included in the contribution analysis. For these extra processes, no differentiation is made between the case studies. The external costs are presented in **FIGURE 11** for three of the 16 case studies. For each of these the costs are shown for the existing reference (for the considered period), the reference for newly built (common practice to date) and the optimised variant. In order not to favour larger dwellings, the results are expressed per inhabitant instead of per m² floor.

For all dwellings, except the ones built before 1945, it was found that transport of the inhabitants contributed most to the life cycle external cost. The transport scenario of an average Belgian family however uses mainly passenger cars and only too a small extent public transport which clarifies this high contribution. It can be concluded that the location of the dwellings is of primary importance for newly built dwellings in the Belgian context. Both for the existing dwelling stock (except the oldest ones) and the newly built ones according to common practice to date (except one apartment), transport is followed by the heating demand as second most important contributor to the life cycle external cost. This phenomenon is strongly pronounced for the detached dwellings (with low thermal compactness). A reduction of the heating demand was thus identified as primary focus (assuming no change in energy production process), beside the building location. To reduce this heating demand, the analysis identified the dwelling type, layout, size and window area as the priorities to focus on, followed by the insulation level and better performing heating systems. For these dwellings (existing and common practice to date) no identical order of the importance of the processes/phases

[7]The electricity consumption was estimated at 5,000 kWh per year, per household (four persons), the daily freshwater consumption at 110 liters/person and the transport of the inhabitants based on an average distance per person, per day in km: passenger car (driving) 21.8 km; passenger car (passenger) 5.9 km; bus, tram or metro 1.5 km and train 3.7 km (based on Hubert and Toint 2002).

FIGURE 11. Three of the analysed dwellings: the external cost of the different processes/phases, expressed in euro per inhabitant—for the existing reference, the solid newly built reference and the optimised variant.



was found which followed heating. Depending on the dwelling the initial phase or electricity consumption were contributing most. Freshwater use and cleaning, maintenance and replacements were identified as contributing to the smallest extent.

The optimised variants resulted in a different picture because no overall priority in contribution of phases/processes could be identified. For some, electricity consumption contributed most, for others it was the initial phase and for others heating remained most important (beside transport of the inhabitants). A further optimisation of these dwellings therefore requires a detailed study.

The analysis of the financial costs pointed out that for all dwellings transport of the inhabitants contributed most to the life cycle financial cost. For some of the oldest dwellings this was followed by heating, for the other existing dwellings by cleaning, maintenance and replacements. Both for the newly built dwellings according to common practice to date and the optimised variants, the cleaning, maintenance and replacement costs were identified as most important (beside transport of the inhabitants), followed by the investment and electricity cost. Heating and freshwater consumption contributed to the smallest extent.

CONCLUSIONS

Although current legislation was proven to be far above the optimum, the analysis of the sixteen representative dwellings in the Belgian context revealed that the passive standard was not always the optimum, neither from an environmental nor financial perspective. The low energy variant or even dwellings with a higher yearly net heating demand than 30 kWh/m² floor were identified as most preferable. In order to make the new legislation from 2020 onwards (passive standard for newly built residential buildings) technically feasible and efficient a well-considered design, orientation and choice of dwelling type will be necessary. A reviewing of the current building regulations moreover seems a prerequisite. Further investigation of the necessary building characteristics to construct efficient passive houses in the Belgian context is needed and this for fixed limiting conditions (e.g. orientation). Important characteristics are for instance the thermal compactness of the building (including separation between rooms at different temperatures) and the size of glazed area for each orientation.

Because many of the existing dwellings proved to lead to a high life cycle external and financial cost due to their high heating demand, energy efficient retrofitting of the existing dwelling stock seems even more important to move towards a sustainable Belgian dwelling stock.

Based on a rough estimation of the external and financial cost of the transport of the inhabitants during use phase, it can be concluded that the location of newly built buildings is of primary importance. The optimisation of single buildings should be combined with a sound urban planning in order to achieve the aim of a more sustainable Belgian dwelling stock.

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