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Life cycle assessment of an apartment building: comparison of an attributional and consequential approach

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Abstract

Life cycle assessment (LCA) as tool to improve sustainability of the construction sector is receiving increasing attention. Different methodological approaches of LCA have already been applied in other research fields, however they have barely been applied on buildings. This study conducts a screening LCA of an apartment located in Buggenhout, Belgium, according to the two main approaches, respectively attributional (ALCA) and consequential (CLCA). Not only the as-built situation is taken into account, but also two brief optimization scenarios are included. The aim is to identify and compare possible differences in results between the two approaches when applied on the same case.
The results indicate a shift in proportions between the different life cycle stages, in particular at the end-of-life stage. However, more important are the differences between individual materials and components, which can result in different proposals for optimization. The two included optimization scenarios support this statement, the first one for the selection of insulating materials and the second one for two different actions to improve energy efficiency (increasing insulation vs. installing a heat pump).

Keywords: Life cycle assessment, CLCA, ALCA, sustainable building, case study

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1. Introduction

In our society buildings are omnipresent, but they inevitably entail negative consequences from an environmental point of view. During their lifespan, they consume plenty of resources and energy, occupy land and at the end they are demolished. As the interest in environmental issues is rapidly growing, also within the construction industry, more attention is being paid to energy efficiency, sustainable housing technologies and construction methods. In the construction sector, this resulted for instance in regulations to decrease energy consumption of dwellings and consequently their ecological burdens i.e., the Energy Performance of Buildings Directive 2002/91/EC (EPBD, 2003) and the revised EPBD 2010/31/EU issued by the European Union [1], [2]. But before any conclusions can be drawn about sustainability, the ecological impact of the whole life cycle has to be investigated, based on the methodology of a life cycle assessment (LCA). Despite the fact LCA takes the entire life cycle into account, still many assumptions and methodological choices have to be made throughout a study, which can lead to different outcomes. Traditionally, attributional LCA (ALCA) and consequential LCA (CLCA) are considered as the two main approaches, however, only in the last few years CLCA is becoming better known and implemented [3].

The aim of this study is to evaluate the environmental impact of a three storey apartment building according to these two main approaches, ALCA and CLCA. Not only the as-built situation but also two brief optimization scenarios will be studied, in order to see if there are differences in priority for improvements depending on the modeling approach. The building under study is a semi-terraced house, designed by Architectenbureau Luc Lodewyckx and is located in Buggenhout in central Belgium (see Fig 1). The built surface is 285 m², the heated volume 1944 m³ and the main facade is south oriented. The calculated yearly energy demand for space heating is between 35,3 and 54,0 kWh/m², depending on the size, lay-out and positioning of the apartment.

2. LCA Methodology

In current practice LCAs are executed according to the framework of the ISO 14040 series [4]. To analyze the environmental burdens of processes, products or services during their entire life cycle and to make it possible to compare different studies, four steps have to be run through: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation [5]–[8]. The first step, goal and scope, defines purpose, objectives, functional unit and system boundaries. One of the strengths of LCA is defining investigated products, processes or services based on their function instead of on their specific physical characteristics. This way, products can be compared that are inherently different, but fulfill a similar function e.g., paper towels versus reusable cotton towels for drying hands. The second step (LCI) consists of collecting, as well as describing and verifying, all data regarding inputs, processes, emissions, etc. of the whole life cycle. Third (LCIA), environmental impacts and used resources are quantified, based on the inventory analysis. At the present time there is a large set of impact categories commonly used, but ISO 14044 states that when the existing categories are not sufficient, new ones can be defined [6]. The fourth and final step is the interpretation of the results [4], [6].

Fig. 1 perspective facade

The approaches to calculate environmental impacts can be subdivided into two main types, attributional and consequential LCA, a choice that depends on the goal and scope definition. Attributional LCA (ALCA) is defined by its focus on describing the environmentally relevant flows within the chosen temporal window (in general, flows of the recent past are examined), while consequential LCA (CLCA) aims to describe how environmentally relevant flows will change in the future in response to possible decisions [9], [10]. From an historical point of view the attributional approach is best known and, certainly within the construction sector, the most applied one. Literature review shows a lack of consequential studies of buildings [11]–[14].

The main difference between the two approaches is related to data collection. ALCA is based on normative rules and uses average data at a certain point in time. It is assumed that all processes are unlinked and do not interact with each other and future projections are based on the extrapolation of current market mixes, with as drawback that the practical feasibility is often neglected. CLCA looks at the marginal changes the system under study causes i.e., the latter looks only at the processes that are actually affected by the system. To identify which processes are affected, it is assumed they are all linked based on the logic of existing economic markets, so activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand (included as essential part of the functional unit). There are multiple mechanisms which can play a role whether a supplier is the marginal one or not. When a supplier is constrained he can not deliver an extra product, this can be because of restrictive regulations or when maximum production capacity is reached. On the other hand, the unconstrained suppliers with the lowest production cost are more competitive on the market and have bigger chances to deliver the additional product as described in the functional unit. In the consequential modeling approach it is also assumed markets are fully elastic on the long term and in general also (slightly) growing. Therefore CLCA is closer to reality as it uses a market-based logic to identify marginal suppliers (the affected suppliers) e.g., when there is a demand for an extra product some producers will be more efficient and competitive and therefore it is more likely they will deliver the product and also some suppliers might be constraint (due to legislation, maximum capacity reached, etc.) and so they are unable to deliver the product [15]–[17]. This difference between approaches generates differences in the field of application whereas the use of averages (ALCA) creates a precise image of current practice e.g., applicable for environmental taxation or the understanding of relations within an existing product chain, while the use of marginal changes (CLCA) is preferred for supporting change-oriented decision-making. When looking at long-term decisions for example, ALCA extrapolates current market mixes whether or not they include constrained suppliers. Even when it is hard to predict what future will bring, it is more likely that a selection of long-term marginal suppliers provides a more realistic image [3], [7], [15], [17], [18].

A second difference is how multi-functionality is handled. In general, ALCA applies allocation and CLCA avoids allocation through system expansion (also referred to as substitution). Allocation can be described as the distribution of the environmental impact over different co-products according to a certain ratio i.e., mass, economic, volume, etc. System expansion avoids such division by including processes affected by an increase or decrease in production of the (dependent) co-products. So when process X produces product A with a dependent co-product B and product B replaces product C on the market, the impact of product A can be calculated as X – C [4], [7]. The latter is in line with the change oriented nature of CLCA as this investigates mainly the influence on affected (marginal) processes. Generally, most authors state that CLCA is more appropriate for decision-making, unless the uncertainties in the
modeling outweigh the insights gained from it, even though ALCA is more frequently used [15], [19].

Another methodological difference between LCAs is how is dealt with recycling, as it is important to avoid double counting. Several ways of modeling are possible, but only the two main ones will be discussed in this section. One possibility is to assign the burdens and benefits to the used materials at product stage e.g., the use of recycled instead of virgin steel. When the end-of-life stage is reached, materials leave the system when they are pre-treated (for instance the demolishing of the building and sorting of materials on site) and ready to recycle, so the actual recycling is beyond the system boundaries and a cut-off is applied. The amount of recycled material in this case is called 'recycled content'. Secondly, the burdens and benefits are taken into account at the end of the life cycle, so all material used in the product stage is assumed to be virgin and recycled materials will replace virgin materials on the market at the end of the lifespan, so system expansion is applied in this case. As the actual recycling has not yet taken place, the amount of recyclable material is referred to as ‘recycling potential’ [20]–[22].

Finally, the earlier mentioned ISO 14040 series describe a general framework, but there have been some other regulatory developments too, specific for the construction sector. For instance, the CEN Technical Committee 350 ‘Sustainability of construction works’ (CEN TC 350) is developing standards for assessing all three aspects of sustainability (economical, ecological, social) both for new and existing construction works and to facilitate the integration of Environmental Product Declarations (EPDs) of construction products. These rules consist in the description of functional equivalent, system boundaries, procedures to be used for the inventory analysis, a list of environmental indicators and procedures for the calculation of the impact categories, rules for reporting and communicating results, etc. This framework is very similar to the one of EPDs, which encourages and facilitates the incorporation of results of external studies [11].

3. Research approach

The main goal of this research is to apply two different modeling approaches on the same case, described in section 1. As the impact assessment is independent of the chosen approach (ALCA vs. CLCA) only one impact method will be applied. To facilitate interpretation of the results there is opted for a single score indicator, the ReCiPe Endpoint method egalitarian version (1.08). The egalitarian perspective is applied since long term emissions are fully included and therefore more comprehensive results are created, while the individualist and hierarchist perspective takes only a shorter timeframe into account. The ReCiPe method was created by RIVM, CML, PRé Consultants, Radboud Universiteit and CML-IA. It implements both midpoint (problem oriented approach; impact categories) and endpoint (damage oriented approach; damage categories) impact categories. The three endpoint categories are normalized, weighted and aggregated into a single score [23]. Previous research pointed out the importance of the choice of impact method as incorporated value choices can affect the results, but since the main goal of this research is to evaluate different modeling approaches, no sensitivity analysis is added by using various impact methods [11], [24], [25]. In first place the main results will be investigated such as total impact and distribution of this impact over the different phases, followed by two brief optimization scenarios.

The first approach is attributional LCA, in accordance with the framework of CEN TC 350 [26], [27]. To ensure comparability with other Flemish studies, an additional guidance which has been followed is a study of the Public Waste Agency of Flanders (OVAM), referred to as MMG, which includes data on transport, end-of-life (EOL) scenarios, etc. representative for the Flemish context [28]. This study aims at providing environmental profiles of building components, following CEN TC 350, but with an extended set of midpoints. The most important aspect of MMG for this research is data on transport distances and scenarios for the Flemish context and data of the end-of-life (ratio incineration, recycling, landfill and additional treatments, etc.). In this approach, the benefits and burdens of recycling are assigned to the product stage (Module A, as described by CEN TC 350) based on the principle of recycled content, so the optional module D is excluded (thus no energy recuperation of waste incineration is taken into account) [26], [27]. The main reason for this exclusion is to make a clear cut between the approaches ALCA and CLCA, as module D creates a strange situation by mixing cut-off with system expansion. The second approach is consequential LCA, so for the product stage materials are assumed to be virgin, but the recycling potential has been taken into account. Similar to ALCA, the main assumptions of the OVAM study is followed. So in general, the quantity of foreground data such as materials, energy, processes and transport is the same for both approaches, only the modeling is different.

Some general assumptions are made and applied on the entire research, in line with the study of OVAM. For building products is assumed they are mainly produced in Europe and transported to Belgium. As many of these product have a large mass compared to their price, it is not likely they follow global markets as proposed in Ecoinvent 3. When no European data is available, other data is used and only the top level data is harmonized to the European situation, such as electricity and market mixes [28]. Only when there is a direct link, a Belgian mix has been used e.g., electricity consumed during the use phase. As this research is a screening LCA, also other simplifications are made, for instance neglecting periodical replacements or maintenance.

4. Results

Both modeling approaches described in the previous section are applied on the same building, a three story apartment located in Buggenhout, Belgium. The building meets the Flemish energy regulations of the period 2012-2013, the timeframe of design and construction, with an estimated yearly energy demand per apartment for space heating between 35,3 and 54,0 kWh/m² [29]. The great difference in energy demand is caused by the differences in size, lay-out, location in the envelope, etc. Some apartments are more enclosed, while the biggest energy demand comes from the biggest apartment located on the upper floor. The first step is to compare the overall results which show a discrepancy of more than 13% of the total impact (see table 1-3 and Fig.2). When distributing the impact over the different phases, it appears the ratio between the phases is completely different. Some of these differences seem logical, for instance the lower impact of the product stage of ALCA due to recycled content of materials or the negative values of end-of-life of CLCA due to system expansion. In addition, when excluding energy consumption, the discrepancy raises to over 20%. The difference between the impact of the use phase is lower, mainly due to an almost equivalent impact of natural gas, used for space heating. The gap of 7,9% can practically entirely be assigned to electrical auxiliary energy.

The previous paragraph showed a difference of over 20% when only considering construction materials. The question now arises whether this affects the ranking of the process contribution, which is much more important compared to the differences in absolute values. Table 4 shows the 20 main contributing materials over the entire life cycle, so excluding the use phase. From the beginning the ranking differs, with reinforcing steel the main contributor

Table 1. LCIA entire life cycle and life cycle stages - CLCA

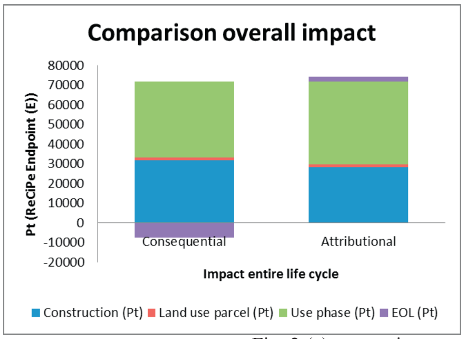
Damage category	Construction (*Pt*)	Land use parcel (*Pt*)	Use phase (*Pt*)	EOL (*Pt*)	Total (*Pt*)
Human Health	10603	-	20981	-1920	29665
Ecosystems	11195	1374	16104	-3528	25145
Resources	9946	-	1650	-1986	9610
Total	31744	1374	38735	-7435	64420

Table 2. LCIA entire life cycle and life cycle stages - ALCA

Damage category	Construction (*Pt*)	Land use parcel (*Pt*)	Use phase (*Pt*)	EOL (*Pt*)	Total (*Pt*)
Human Health	10021	-	21881	1248	33150
Ecosystems	10234	1374	17120	813	29540
Resources	8072	-	3040	429	11542
Total	28327	1374	42041	2490	74232

Table 3. Comparison impacts entire life cycle and life cycle stages CLCA vs. ALCA

	Construction (%)	Land use parcel (%)	Use phase (%)	EOL (%)	Total (%)
Ratio CLCA/ALCA	12,1%	0,0%	-7,9%	-398,6%	86,8%
Ratio CLCA/ALCA excl. Use phase			79,8%		
Ratio CLCA/ALCA only Use phase			92,1%		



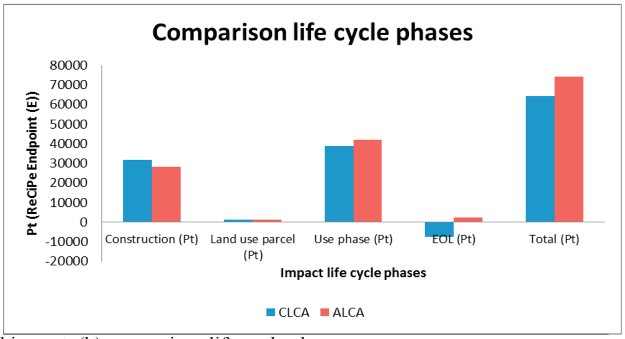


Fig. 2 (a) comparison overall impact; (b) comparison life cycle phases

for ALCA and bricks for CLCA. In addition, major differences can be seen at aluminum window frames
, ceramic tiles and to a lesser extent cement based products e.g., concrete, mortar and screed. When comparing the differences between these materials, it is interesting to note the difference of impact per kg, which can go as high as 890% for aluminum. Or when looking at the difference in overall impact, aluminum frames are responsible for 39 % of the discrepancy between the two approaches. Ceramic tiles and rigid PUR sheets are two exceptions in this ranking with a lower impact for ALCA. The differences between the two approaches can be explained on multiple ways, depending on the type of the materials. Metals are quite obvious as it is described in section 2: the recycling potential (CLCA) of metals entails a huge environmental saving due to the high quality recycling possibilities, which is higher than the benefits of the recycled content (ALCA). A similar reasoning can be applied on inert materials. The impact of the production is almost equal as there is no recycled content in bricks, cement or concrete, but in the consequential approach the materials can replace virgin gravel in road bases, instead of the assumed landfill in ALCA. The difference in impact of ceramic tiles is a bit more complex, as it is related to a multiple-output process. A lot of heat is needed during production, which is delivered by an installation for heat and power co-generation. ACLA applies allocation based on caloric value, so most of the impact is assigned to the electricity production, while in the consequential approach the produced electricity is substituted by the marginal production (with a rather low impact) so the impact of the heat production is much higher compared to ACLA.

To illustrate the relevance of differences in the process contribution, two brief optimization scenarios are elaborated, one based on material choices, one based on energy strategies. The first scenario compares different insulation materials, as has been done in other studies but only for an attributional approach so far [30]. The functional unit in this case is the thermal performance of the materials - a U-value of 0,3 W/m²K is the reference - and an equal technical life span is assumed. Table 5 shows the different properties of the materials which are used to calculate the required mass per square meter. Only looking at the product stage, the ranking of the two approaches is completely different: rockwool, EPS, PUR for ALCA versus EPS, rockwool, PUR for CLCA. When taking also the end-of-life treatment into account, differences are less distinct but still present i.e., glass wool and EPS switch positions.

The second optimization scenario is more complex. Instead of a pure material ranking, two different actions to improve energy efficiency of the building are compared. On one hand increasing the thickness of the PUR insulation

Table 4. Process contribution

Process name	CLCA		ALCA		Comparison	
	Total (*Pt*)	Total (*%*)	Total (*Pt*)	Total (*%*)	ALCA/CLCA (*%*)	Δ (ALCA-CLCA)$_{proces}$ / Δ (ALCA-CLCA)$_{life\ cycle}$
Reinforcing steel	3073	13,2%	4550	15,4%	48,1%	23,3%
Brick	3184	13,7%	3587	12,1%	12,6%	6,3%
Polyurethane, rigid foam	3156	13,6%	3118	10,5%	-1,2%	-0,6%
Window frame, aluminium	280	1,2%	2776	9,4%	890,4%	39,3%
Concrete block	1752	7,5%	1961	6,6%	11,9%	3,3%
Ceramic tile	2332	10,0%	1663	5,6%	-28,7%	-10,5%
Cement cast plaster floor	1301	5,6%	1520	5,1%	16,8%	3,4%
Poor concrete	880	3,8%	1429	4,8%	62,5%	8,6%
Cement mortar	1159	5,0%	1395	4,7%	20,3%	3,7%
Steel, low-alloyed	723	3,1%	1276	4,3%	76,5%	8,7%
Laminated safety glass	782	3,4%	847	2,9%	8,3%	1,0%
Bitumen seal	624	2,7%	591	2,0%	-5,4%	-0,5%
Alkyd paint, without solvent	460	2,0%	559	1,9%	21,4%	1,6%
Base plaster	366	1,6%	434	1,5%	18,6%	1,1%
Concrete, normal	226	1,0%	360	1,2%	59,6%	2,1%
Aluminium alloy, AlMg3	251	1,1%	318	1,1%	26,6%	1,0%
Adhesive mortar	291	1,2%	306	1,0%	5,0%	0,2%
Flat glass, uncoated	214	0,9%	254	0,9%	18,5%	0,6%
Polyethylene, low density	220	0,9%	228	0,8%	3,8%	0,1%
Concrete, normal, prefab	164	0,7%	205	0,7%	25,0%	0,6%

with 2 cm, on the other hand adding an earth-water heat pump for space heating. The extra electricity consumption of the heat pum

p is provided by the Belgian electricity mix of the grid. The first scenario with the extra insulation requires additional material during the construction phase which entails an increase of the impact, but still the benefits of energy savings

are greater. As demonstrated in table 6 and 7, the results of ALCA and CLCA are quite close to each other. The main reason for the difference is due to the PUR, as the impact of natural gas is more or less the same for ALCA and CLCA. On the other hand, the second scenario shows a great difference in results, which can be explained as a cumulative effect of different aspects. First, heat pumps consist for a great part of metals, steel and copper in particular, which have a much lower impact in CLCA due to the benefits of recycling. A second reason is the shift in type of energy. A heat pump uses electricity to increase the temperature of an energy carrier while energy is extracted from the soil, with the Coefficient of Performance (COP) as an indicator of the efficiency (in this case an earth-water heat pump for floor heating with a COP of 4,9 has been applied). This means a conventional heating system using natural gas can be replaced by a heat pump, resulting in a saving of natural gas. On the other hand, the latter comes with an increase of electricity consumption, be it to a lesser extent, but in this case it is a dominant factor. For electricity production there is a big difference between averages and marginal suppliers, the impact for 1 MJ is about 80% higher in the attributional approach for the Belgian context, because of the marginal suppliers …. These two aspects explain why the heat pump scenario is clearly preferred for CLCA, while ALCA only shows a slight preference for the same scenario. So the results show clearly the importance of making the right choices in the goal and scope stage, as using the wrong approach for developing optimization strategies may lead to incorrect guidelines.

5. Discussion and recommendations

The results show the effect of the choice of a modeling approach, but there are some limitations as well. First, this

Table 5. Optimization scenario 1: insulation materials

Material	material properties			Production (*Pt*)		EOL (*Pt*)		Total (*Pt*)	
	λ_D (*W/mK*)	d (*m*)	mass/m² (*kg/m²*)	ALCA	CLCA	ALCA	CLCA	ALCA	CLCA
Rock wool	0,034	0,11	7,9	0,93	1,00	0,04	0,04	0,97	1,03
Glass wool mat	0,032	0,11	3,5	1,16	1,24	0,02	0,02	1,18	1,26
Polystyrene, foam slab (EPS)	0,038	0,13	1,9	0,98	0,94	0,35	0,27	1,33	1,21
Polyurethane, rigid foam (PUR)	0,023	0,08	2,3	1,13	1,15	0,43	0,33	1,56	1,48
Polystyrene, extruded (XPS)	0,033	0,11	3,3	1,51	1,53	0,61	0,48	2,12	2,01

Table 6. Optimization scenario 2a: increased insulation

	mass (*kg*)	Energy (*MJ*)	CLCA (*Pt*)	ALCA (*Pt*)
Additional PUR (2 cm extra)	189,1	-	221,1	233,0
Reduced enegy consumption (60 year)	-	-2963,8	-632,9	-633,4
total			-411,9	-400,4

Table 7. Optimization scenario 2b: heat pump

	number replacements	Energy (*MJ*)	CLCA (*Pt*)	ALCA (*Pt*)
Material - Heat pump	3	-	1624,5	3929,1
Auxiliary energy heat pump (60 year)	-	32236,9	10999,2	19891,8
Reduced enegy consumption (60 year)	-	-113682,9	-24278,4	-24293,4
total			-11654,7	-472,5

case study is a screening LCA and a starting point for future research, so the results should be interpreted with care. Alt

hough they can not be used literally without critical review, the common trends and results do prove the importance of assumptions and modeling approaches of LCA (ALCA vs. CLCA). A second limitation is the calculation of the energy consumption with a static simulation, executed with the official Belgian EPB-software 3G version 5.0.2. In future research, a dynamic simulation can be used to improve the level of detail of the simulations, still the influence is assumed to be limited because the calculated energy consumption is the same for both approaches. To ensure the robustness of the results, in future research more attention should be paid to the selection of the impact methods by integrating midpoint categories as well. Finally, the study has made use of Ecoinvent 3 and notwithstanding that adjustments have been made to ensure the used data is representative for the Flemish context, the marginal suppliers have been adopted as defined in Ecoinvent 3.

In general, this paper tries to point out the importance of modeling assumptions of an LCA study especially when the results will be used to develop optimization scenarios. Even though the attributional approach is not suitable for supporting decisions and their future influence, it is the most commonly used way of executing LCAs. More attention has to be paid to the goal and scope, so from the start an educated chose can be made between ALCA and CLCA. In addition, more research has to be done in the field of CLCA. Ecoinvent 3.0 is already a step in the right direction, but in particular for the construction sector, many materials do follow local markets due to a high mass per monetary unit of some of the common materials e.g., inert materials, and the differences in building tradition and climate.

6. Conclusion

A screening LCA of an apartment in Buggenhout, Belgium, was carried out according to an attributional, as well as a consequential approach. The main goal was to compare the difference in results of these two approaches rather than to perform a detailed LCA. In addition some simplifications have been made but since they are identical for both approaches, their influence is assumed to be limited. Looking at the overall results, it is clear there is a shift of proportion between the impacts per building stage. In general, CLCA rewards high-quality recycling much more and also assigns a lower impact to electricity consumption which is clearest at the use phase - due to the (electrical) auxiliary energy CLCA has a lower impact of the use stage of almost 8% - and at end-of-life stage - recycling generates a negative impact for the total end-of-life for CLCA.

Even more important than the shift between life cycle stages are the differences between individual materials or components. A ranking of materials contributing most to the overall impact already gives an indication of the discrepancies between the two approaches, but this becomes more clear by execution two brief optimization scenarios. The scenario of a pure material optimization shows a different ranking of the three best performing insulation materials and for two proposals to improve overall energy efficiency, CLCA strongly favours the implementation of a heat pump over adding extra insulation while for ALCA the possible benefits are more or less the same. This clearly illustrates the importance of methodological assumptions of an LCA, since different optima arise even though the case is exactly the same. Since the results are based on a screening LCA, more research is needed to improve the robustness of the results by increasing the level of detail, formulating maintenance scenarios and improving knowledge of the marginal suppliers specific for the Flemish context.

Finally, to enhance a sustainable society it is needed that policy is focused on the entire life cycle of buildings instead of merely on energy efficiency, but this should happen in a proper manner with the right choice of approach depending on the specific objectives. Unfortunately currently this is not the case in the construction sector, which mainly focuses on attributional LCA.

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