Title

Cradle-to-grave life-cycle assessment within the built environment: Comparison between the refurbishment and the complete reconstruction of an office building in Belgium

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Abstract

In the current context of the necessary sustainability transition of the built environment, it is widely recognized that buildings are a major contributor to the energy consumption of fossil fuels and the emission of CO_2. Most of the debates, policies and research are however dedicated to the sole construction of new very efficient (up to zero-energy) building, neglecting the potential of actions on the existing building stock. In this context, we argue that LCA tools are of a huge interest to objectivize the need to refurbish old buildings, in order to increase their energy efficiency and extend their life span, and to compare this strategy to the demolition / reconstruction of buildings. To achieve this aim, this paper aims at updating an existing tool that enables to carry out the life cycle assessment of buildings, by taking into account demolition and construction phases. Then, the tool is applied to one case study of the low-energy refurbishment of a public office building in Brussels, to compare the impacts of the complete demolition followed by a complete reconstruction (rebuild project) to the retrofitting of the existing building (retrofit project). Our main findings confirm the huge impact of the use phase, highlight the impact (energy and CO_2 emissions) of the construction and demolition phases and show that the in-depth renovation of this building leads to lower environmental indicators compared to its full reconstruction. The tool and results provided in this paper support the development of policies in favour of the retrofitting of the existing building stock and highlight the importance of including the whole life cycle of the building in the analysis.

Keywords

Life-cycle analysis, tool, demolition, reconstruction, refurbishment, retrofitting, end of life

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1. Introduction

Energy uses in the building sector represent around 40% of the total energy used in Europe (European Commission 2015), representing the most important sector, before transportation and industry. Reducing energy consumptions in the building sector is hence a major challenge to mitigate climate change. It has been recognized as an important policy target and progressively integrated into regulation frameworks, at the European, national and regional levels. Today, most efforts are concentrating on the construction of zero-energy buildings and on the reduction of the energy uses during the use phase of existing buildings through a better insulation. The Directive on the Energy Performance of Buildings (2002) that was implemented in 2002 aimed at enhancing energy efficiency in the building sector by establishing minimum standards on the energy performance of new buildings, and existing buildings larger than 1,000 m² that are subject to major renovation. In 2010, this Directive was revised (EPDB 2010) so that all new buildings built by 2020 (2018 for public buildings) should be nearly zero-energy buildings. Although guaranteeing the construction of energy efficient buildings and the energy efficient retrofitting of large buildings, this directive does not address the major challenges related to the retrofitting of the existing building stock. In the scientific literature also, much more attention is put on operational energy efficiency, than on the assessment of embodied energy and carbon (Pomponi and Moncaster, 2016). The challenge of embodied energy / carbon is however particularly important in numerous European countries, where the renewal rate of the existing building stock is quite low (Ma et al. 2012; Nemry et al. 2010, Office of Climate Change 2007; Reiter and Marique 2012; Roberts 2008). To illustrate this low rate of renewal, in the UK for example, 87% of existing homes are expected to be standing in 2050 (Boardman, 2007). Because of the age and low energy performances of the existing building stock, it is today essential to objectify the interests of refurbishment works in a view to extend the energy efficiency and the life span of buildings, but also in comparison with the demolition of old buildings and their complete reconstruction, taking into account the use phase of the building as well as construction and demolition operations, that are often overlook in current LCA research.

In this context, the paper starts with a synthetic state of the art about demolition and refurbishment works in general and the interest of LCA tools to investigate this research question in particular. Afterwards, the updating of the LCA tool developed by Rossi et al. (2012) to take into account the impacts of demolition phases (before reconstruction and at the end of life of the building) and construction phases is presented. The updated tool is used to study the refurbishment of the case study building (*retrofit* project), built in 1934, located in Brussels (Belgium) and to compare the results to its complete demolition and reconstruction (*rebuild* project). The main findings and perspective for further research are finally summarized in the last section of this paper.

2. State of art: demolition versus refurbishment

The issue of whether to demolish or refurbish old and/or poorly insulated buildings has been debated for over a century (Power 2008) but the evidence on whether demolition/reconstruction or refurbishment of existing buildings would be the most environmentally sound is unclear. Power (2008) argues that upgrading the UK building stock to high environmental standards can be achieved at a lower cost than demolishing it, and with as significant carbon reduction. Also mentioned by Power (2008), the German Federal Housing, Urban and Transport Ministry has announced an ambitious energy reduction programme that will upgrade all pre-1984 homes in Germany by 2020 (an estimated 30 million units). This programme is based on the outcomes of several CO_2 reduction programmes since 1996, showing the feasibility of retrofitting. An 80% cut in energy use was achieved, making the performance of the renovated homes at least as good as Germany's current new building standards. Branders et al. (2010) explain that the decision to demolish or to retrofit an existing building depends upon numerous factors such as the initial state of the building, the targeted energy performances or the aesthetic and patrimonial quality of the building. Very few studies (e.g. Dubois and Allacker, 2015) conclude that significant reductions in CO_2 emissions can only be obtained through demolition / reconstruction of buildings. Boardman (2007) suggest to increase the current rate of demolition (stock turnover) of inefficient houses, in the UK context.

To objectivise the interest of refurbishment versus demolition/reconstruction of existing buildings, from an environmental point of view, the use of LCA tools seems of huge interest. The general LCA methodology is well defined in the ISO norms (ISO, 2006a and 2006b). Despite some current limitations of LCA, namely summarized by Pomponi and Moncaster (2016) on the basis of a systematic literature review, LCA tools are recognized as one of the best tools for environmental assessment of products and processes (Crawford, 2008) and are thus widely used in various domains related to the sustainability of built environments (e.g. biogas power plants (Erikson et al., 2016, Iordan et al., 2016), wastewater treatment (Lim and Park, 2009, Opher and Friedler, 2016, Pretel et al., 2016), residential water-using appliances (Lee and Tansel, 2012), waste management (e.g. Bovea and Powell, 2006), wood utilization (Höglmeier et al., 2015), pavement infrastructures (Inyim et al., 2016), urban transportation (Kliucininkas et al, 2012), materials (Hong et al., 2012; Kohler, 1995; Turk et al., 2015, Vieira et al., 2016)). LCA has also been identified as a promising framework for the environmental assessment of territories (Loiseau et al., 2012) or urban blocks (Stephan and Athanassiadis, 2017). LCA tools, specifically dedicated to buildings, have also progressively emerged as practical tools to assess and compare the environmental impacts of different scenarios, in the current debates about energy efficiency of our built environment. These LCA tools have today mainly been used to evaluate energy consumptions and/or greenhouse gas emissions in buildings, during the use phase or along the whole life-cycle of the building (e.g. Ji et al., 2014; Asif et al., 2007, Kofoworola and Gweewala, 2008). A great number of studies have been achieved on the development of LCA tools and on their application to buildings. And several review papers have recently been published to summarize the evolution, interests, limitations and results of buildings LCA (e.g. Bribian et al 2009; Buyle et al 2012; Cabeza et al 2014; De Boeck et al 2015; Dixit et al 2010; Karimpour et al 2014, Sartori and Hestness 2007, SETAC 2003). But, as stated by Pomponi and Moncaster (2016), even if incomplete assessment is better than no assessment (Hertwich et al., 2000), extra care is required when using and comparing results from published LCAs, which might be both partial and short sighted, due to the current limitation of these tools.

Amongst their numerous advantages, these LCA approaches can account for a large number of parameters that are known to act on the energy consumptions of a system and can be used to examine the influence of several energy efficiency strategies. However, as highlighted by Gaspar and Santos (2015), LCA of buildings mainly concentrate on the analysis of new and very efficient buildings, most of the time neglecting the existing building stock. Moreover, most studies dealing with the refurbishment of buildings only compare the environmental gains in comparison with the initial building, and not with a new equivalent construction (Ferreira et al. 2015). Using LCA to compare refurbishment scenario to demolition/reconstruction scenario has currently not yet been achieved and the assessment of demolition, construction and end-of-life phases (including the recycling phase) in buildings LCA has yet been assessed.

In his analysis of a residential building in Turin (Italy), Blengini (2009) considered the pre-use phase (production and transportation of materials), the use phase and the end-of-life phase (recycling and elimination of waste) and concluded, in this case, that the use phase is the most harmful one. This result is also highlighted in other papers related to existing buildings (Ferreira et al. 2015; Rossi et al. 2012; Sartori and Hestness 2007). Recent studies related to new buildings have however highlighted that when high energy consumption standards (such as the passive standard, the (nearly) zero-energy standard or even the positive standard) are reached, this general trend is reversed. In this case, the other environmental impacts (related to the construction phase for example) become significant (Andrade 2010). It also worth mentioning that the assessment of the embodied energy in buildings can vary substantially, especially due to a quite high variability in the cradle-to-gate materials data (although those differences usually remain tolerable (Blengini 2009)), the local energy mix (Rossi et al. 2012) or the chosen service life time (Sartori and Hestness 2007; Wallhagen et al. 2011).

Ortiz et al. (2010) studied an apartment building located in Barcelona (Spain). They assessed the impacts of the construction phase (fabrication and transportation of materials, energy use for equipment and waste management) and compared several types of internal and external walls as well as several scenarios dealing with the management of waste (dump, burning, recycling).

Several studies have assessed the environmental impacts of refurbishment works in comparison with the initial situation, and conclude that refurbished buildings have lower life cycle impacts than the initial solution. For example, in Ardente et al. (2011), LCA approach was used to assess the environmental impacts and energy efficiency of several types of refurbishment and to highlight the significant benefit of (1) improving the envelope thermal insulation, (2) replacing lighting and glazing components, and (3) renovating the heating, ventilation and air-conditioning (HVAC) plants. Whereas, in Assiego de Larriva et al. (2014), a LCA was used to quantify the environmental benefits of five refurbishment scenarios with the initial situation, putting a particular emphasis on the comfort of occupants. In the Chinese context, Li and Colombier (2009) also concluded that improving building energy efficiency can led to considerable CO_2 emissions reduction.

Amongst the few studies comparing demolition and/or refurbishment with the construction of a new building equivalent in terms of size and/or functions, Gaspard and Santos (2015) concluded that, for their case study house located in Southern Europe, the refurbishment was a more sustainable strategy because the quantity of materials and, hence, embodied energy was lower. Ferreira et al. (2015) studied a heritage building in Lisbon (Portugal) and also highlighted that structural refurbishment works are more sustainable than the construction of a new equivalent construction (with a similar architecture and similar demands and project constraints).

More broadly, as stated by Pomponi and Moncaster (2016, p. 693), extending the life span of building through refurbishment would also intuitively delay and therefore reduce energy uses and CO_2 emissions associated with deconstruction and demolition which have been investigated in few studies (e.g. Densley Tingley and Davidson, 2011; Toller et al, 2011; Yung and Chan, 2012).

3. The LCA tool

3.1. The initial tool

Rossi and al. (2012) developed a tool that enables the life-cycle analysis of residential buildings, under different climate, from cradle to gate. This tool follows the recommendations of the ISO Standards 14000 series (ISO 2000, 2006a, 2006b) and permits the evaluation of the embodied energy (and embodied equivalent CO_2 emissions or, namely, "Embodied carbon") including the transport phase of all materials to the site, and yearly energy consumption of residential buildings. For each location, a different set of original data can be taken into account. The energy consumption, being for heating space or water, for cooling or for lighting is (via the energy mix for electricity amongst other) transformed into CO_2 emissions to deduce the "Operational carbon" (use phase) as well. The influence of the energy mix can therefore be assessed. The non-metallic materials databases used in this tool are CRTI (Luxembourg Construction portal, www.crtib.lu), CML 2001, inies.fr and ICE – University of Bath databases providing energy consumption and equivalent CO_2 emissions for a quite wide amount of construction materials in Europe, as well as BEES database (http://ws680.nist.gov/bees/). The procedures, assumptions and data sets used to calculate the Embodied and Operational energy and carbon are extensively developed in Rossi et al. (2012).

In a companion paper (Rossi et al 2012b), this tool was applied to a residential building located in three different European towns: Brussels (Belgium), Coimbra (Portugal) and Luleå (Sweden). A different life-cycle scenario was taken into account for each location, in which the monthly temperatures, energy mix, heating and cooling systems were defined. The LCA results obtained with the tool for Brussels were verified against Pleiades+Comfie and Equer software. The results of this case study confirmed that, for all the three climates, the Operational energy was the most harmful period during the building life-cycle. Moreover, the energy mix of the country strongly influenced the equivalent CO_2 emissions related to the use phase (Operational carbon) and may entirely reverse the conclusions about the life-cycle carbon footprint of the building. The initial tool was also used to compare a steel load-bearing system to a concrete load-bearing system.

3.2. The updated tool

In this paper, the initial LCA tool developed by Rossi et al. (2012) was updated to allow for a comparison between the demolition of a building followed by its complete reconstruction (*rebuild* project) and the refurbishment of the existing building (*retrofit* project). In this updated tool, the user should prepare a relatively thorough bill of materials, wall by wall, including a description of each window and their orientations. The different elements (external walls, floors, roofs, internal partitions, doors and windows) of the building are then automatically sorted and summarized in four main parts: (1) the finishing, (2) the roof, (3) the concrete structure (if any) and masonry and (4) the steel structure (if any). For each of these four parts, it is possible to specify if and how it will be demolished, replaced or refurbished. The material databases used in the analysis were presented in Rossi et al. (2012).

Three main life-cycle phases were included:

- (a) The demolition phase of parts or of the whole building, before their reconstruction;
- (b) The construction phase to rebuild or to retrofit the building;
- (c) The demolition phase at the end-of-life of the building.

The updated tool allows assessing the energy consumption and equivalent CO_2 emissions of the transportation phase (travel of workers, from home to construction site; travel of material, from extraction site to construction site; and waste, from demolition site to landfill) in the energy balance, based on the method developed by Marique and Reiter (2012). For each phase, the user can specify how the transport of workers is organized (number of vehicles, travelled distances and consumption of the vehicles can be specified) and how much time (in working days) each phase takes. For example, if only the roof of an existing building would be replaced, the tool would take into account (a) the demolition of the existing roof, (b) the construction of the new roof and (c) the demolition at the end-of-life of the new roof.

The assumptions used to calculate the impacts related to the vehicles (transport of workers) and three equipment used to deconstruct and build are summarized in Table 1.

Table 1: Assumptions used to take into account the environmental impact of vehicles and equipment (the interested reader can also refer to Marique and Reiter (2012) for the method and to Dujardin et al. (2014) for the data):

	MJ/days	kg CO_2/days	MJ/km	kg CO_2/km
Small deconstruction / dismounting equipment	82.8	5.96		
Tower crane (30 tons)	4,348.8	312.99		
Loading crane (20 tons)	5,184	373.10		
Vehicles (diesel)			3.17	0.26

To summarize, based on the assumptions, database and methodology presented in Rossi et al. (2012), the updated life-cycle assessment tool comprises the assessment of the following aspects:

- Production of materials:
    - Extraction of raw materials
    - Transportation of materials from extraction site to the production plant
    - Fabrication / transformation of materials into construction products

- Transportation of products from the production plant to the construction site and from the construction site to the waste disposal site (in the eventuality that some materials cannot be recycled).
- Demolition phase:
    - Home-to-work travel of workers
    - Use of small deconstruction / dismounting equipment
    - Use of heavy equipment (e.g. cranes), especially when heavy demolition is needed
- Refurbishment / Construction phase:
    - Home-to-work travel of workers
    - Use of (small and/or heavy) equipment
    - Loss of 5% of the materials
- Use phase, as assessed in the initial tool (Rossi et al. 2012).
- End-of-life phase (cut-off method): impacts related to the landfill of dumped materials.

Two impacts are assessed and discussed: the global warming potential (GWP), developed by the Intergovernmental Panel for climate Change in order to take into account the impact of greenhouses gas emitted in the atmosphere (expressed in kg of equivalent CO_2 per square meter of usable surface) and the energy consumption (direct and indirect) of a product (here the building) throughout its life-cycle (expressed in MJ or kWh per square meter of usable surface).

4. Presentation of the case study

4.1. Reference building and urban context

For the purpose of this study, a reference building was chosen as functional unit. The reference building is an office building, built in 1934. This building is located in Brussels (Belgium), in a protected area (close to an old abbey) but is not protected itself, in spite of its interesting architectural qualities. It is located on a corner, between two streets (Figure 1). Since 2005, the building has been occupied by the local public centre for social assistance.

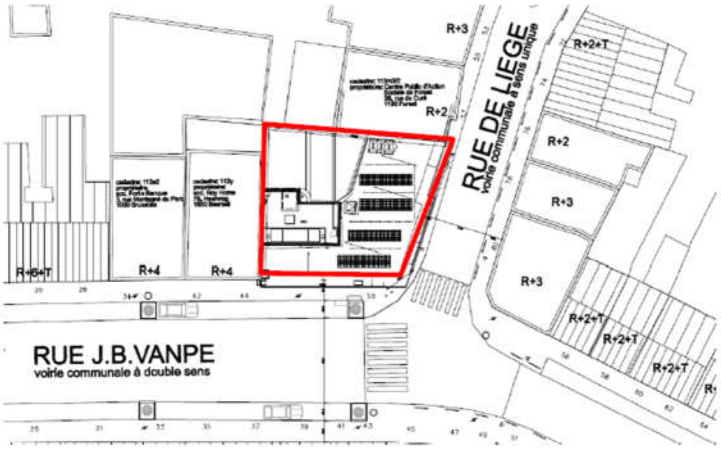

Figure 1: Implantation of the building in its urban context

Before renovation, the building had a heated surface area of 756m² and a volume of 2,330m³. It contained 3 levels, including a semi-underground level. This underground level comprised the archives, technical rooms, the kitchen, restrooms and a large meeting room. A small courtyard brought light to the rooms located at the rear side of the building. The ground floor was composed of the office rooms, a meeting room and a green terrace. Also including offices, the restrooms were present on the level 1. Appendix 1 presents a picture of this building before any retrofitting works had occurred.

4.2. The *retrofit* project

The public authority, occupying the building since 2005, wanted to retrofit it for wholesomeness and security reasons. In this retrofitting process, two aspects were particularly important: (1) to maintain the architectural quality of the building, to keep the architectural aspects of the external facades intact; and (2) to drastically reduce the energy consumptions. Moreover, an extension of the surface area was needed.

The main volume of the building was preserved but the internal spaces were reorganized to be in agreement with the new comfort and utilization standards. A new level (level 2) and two technical annexes (a technical room for the ventilation devices, located on the roof and an additional room on the ground floor) were added to the initial building (see Appendix 2 and 3). A new green roof above the meeting room was added.

In the retrofit project, the architects (A2M, an office specialized in energy retrofitting of buildings) proposed to maintain the external facades and the main staircase of the building and to deeply retrofit its envelope (internal skin of the walls and roofs) in order to meet the “very low energy” standard (energy requirements for heating lower than 30kWh/m².year). To meet these requirements, the envelope was cautiously insulated and a new ventilation system (mechanic exhaust with heat recovery) was installed. To maintain the architectural aspects of the street facades, it was necessary to insulate the street facades via the inside. Therefore, to avoid thermal bridges reducing the energy performance of the envelope, the slabs were separated from the external walls, all around the whole periphery of the street facades. On the one hand, steel beams and columns were installed to ensure their stability. On the other hand, metal rods were placed to join the street façade (disconnected of the building) to the aforementioned building structure, minimizing the thermal bridges. Ten centimetres of polyurethane (PUR – a rigid insulation foam widespread used as insulation material in buildings for its thermal conductivity and its light weight) were added to insulate the façade, internally. The new walls (level 2) were also insulated similarly while the slab was insulated via 8 centimetres of PUR and the roof using 20 centimetres of mineral wool. On the roof of the new technical room, 15 centimetres of PUR were used. All existing window frames were replaced by new energy efficient frames with triple glazing. The rear façade was insulated via the exterior and a new coating was proposed to enhance its aesthetic appearance. The new heated surface area of the building and the new heated volume equal 1,012m² and 3,050m³, respectively.

Appendix 2 and Appendix 3 respectively present the plans and section of the retrofitted building (adapted from A2M (2011)): and a picture of the retrofitted building (A2M 2011).

4.3. The *rebuild* project

For the purpose of this study and to allow for a comparison between renovation and demolition/reconstruction, a demolition/reconstruction scenario is proposed. In this scenario, we consider that the existing building is totally demolished and that a brand new building is rebuilt. The reconstructed building presents the same characteristics than the retrofitted building as far as heated surface area, volume, number of levels, thermal performances of the envelope and ventilation system are concerned. The walls are made of 190 millimetres (mm) of concrete blocks insulated with 100mm of PUR and covered with cladding brick of 90mm~~m~~.

4.4. Specific assumptions regarding both case studies

Here below, one can find particular assumptions related to the presented case study:

- The walls respect the thermal transmittance value (called U-value in the Belgian regulations, in W/m^2K) recommended by the Belgian regulations, with an average of $U=0.35\ W/m^2K$.
- The difference between the heat loss factor (called UA in the Belgian regulations) (about 530 W/K) and compactness (about 2.04) of both buildings is negligible. The general thermal insulation of the building (defined in the Belgian regulations as the "K value", taking into account the geometry of the buildings and the level of insulation of walls, roofs, windows and slabs) of the new building equals K23 and K26 for the renovated one.
- The anticipated lifetime of the building (either retrofitted or demolished and reconstructed) is 50 years. During this period, no maintenance is foreseen (no elements are replaced).
- The comfort temperature during the day in the summer (winter) is 23.0°C and 21.0°C (respectively winter). During the night, the minimal temperature is set to 16.0°C.
- 70% of the year is considered as working day with 8 hours of working hours per day and 20 users.
- An urban factor (shadow factor on the windows) of 0.6 is considered in the present analysis leading to a total yearly solar gain of 13,337kWh.
- The air change rate for the retrofit project is set equal to 0.7, which is slightly higher than for the rebuild project for which a value of 0.5 was chosen. This difference is due to the higher probability to have a less leakage resistant envelope in the first case.
- The Electricity Belgium mix is used.
- As presented in Rossi et al. (2009), to calculate the operational energy, the space heating (natural gas), the ventilation losses, the hot water energy uses, the human/devices heat production and the solar gains are included. Considering that, it can be concluded that, for both scenarios, the impacts of the use phase is almost exactly the same. Additional consumption related to rebound effect, as defined by Rovers (2014) is also considered as similar in both cases.
- Except for metallic materials for which a distance of 250 km is considered, the transport distance to the construction site is 50 km. Each material is transported via road.

The assumptions presented in the following tables are considered, respectively for the construction / reconstruction phase (Table 2), for the demolition of the roof and the finishing in the retrofitted project (Table 3), for the demolition of the existing building in the rebuilt project (Table 4) and for the demolition, at the end of the life, in both projects (Table 5). The data summarized in these tables were determined after consulting architects involved in similar (retrofit or rebuild) projects in Belgium.

Table 2: Assumptions considered for the construction / reconstruction phase (both projects)

	Duration in days	Number of vehicles	Distance in km	Equipment considered
(1) Finishing	135	3	45	Small deconstruction/dismounting tools
(2) Roof	32	1	45	Small deconstruction/dismounting tools and Loading crane (20 tons)
(3) Concrete structure and masonry	83	2	45	Small deconstruction/dismounting tools and Loading crane (20 tons)
(4) Steel structure	5 (0 for the new construction)	1	45	Small deconstruction/dismounting tools and Tower crane (30 tons)

Table 3: Assumptions concerning the demolition of the roof and the finishing for the retrofitted project

	Duration in days	Number of vehicles	Distance in km	Equipment considered
(1) Finishing	10	2	45	Small deconstruction/dismounting tools
(2) Roof	10	1	45	Small deconstruction/dismounting tools and Loading crane (20 tons)

Table 4: Assumptions concerning the demolition of the existing building for the rebuilt project

	Duration in days	Number of vehicles	Distance in km	Equipment considered
(1) Finishing	10	2	45	Small deconstruction/dismounting tools
(2) Roof	10	1	45	Small deconstruction/dismounting tools and Loading crane (20 tons)
(3) Concrete structure and masonry	20	2	45	Small deconstruction/dismounting tools and Loading crane (20 tons)

Table 5: Assumptions concerning the demolition at the end of the life, for both projects

	Duration in days	Number of vehicles	Distance in km	Equipment considered
(1) Finishing	10	3	45	Small deconstruction/dismounting tools
(2) Roof	10	1	45	Small deconstruction/dismounting tools and Loading crane (20 tons)
(3) Concrete structure and masonry	25	2	45	Small deconstruction/dismounting tools and Loading crane (20 tons)
(4) Steel structure	5 (*)	1	45	Small deconstruction/dismounting

	tools and Loading crane (20 tons)

*0 for the new construction

5. Results and discussions

The LCA tool was then used to study the case study presented in Section 4, to compare retrofitting works with the complete demolition/reconstruction of the building, on a whole life-cycle basis. The difference between two indicators are assessed and discussed: the global warming potential (GWP), expressed in kg of equivalent CO_2 per square meter of usable surface and the energy consumption of the building throughout its life-cycle (expressed in MJ or kWh per square meter of usable surface).

5.1 Impact of the use phase

As stated in Section 3, the thermal insulation level (level K in the Belgian regulation) reached in the two scenarios is similar, in order to compare the retrofitting of the existing building with its complete demolition / reconstruction, on the same basis. The impact of the use phase is hence the same for the two considered projects (the maximum relative difference between both impacts during the use phase of the building is 2%). This thermal insulation level equals K23 (K26 for the *retrofit* project), which means that the energy performances of the retrofitted / rebuilt building, during the use phase, are relatively good in comparison with existing buildings and standards imposed by the European Directive on the Energy Performance of Buildings. Between May 2010 and December 2013, in Belgium, buildings built had to present a thermal insulation level K lower than K45. The regulations were then strengthened, with a maximum thermal insulation level fixed at K35.

In accordance with previous research, the *space heating* demand takes a relatively high importance of the total impacts. For the *retrofit* (respectively *rebuild*) project, it is indeed 3.2 (resp. 1.2) times higher than the total embodied energy impacts (demolition, materials, transport, construction and end-of-life) and 1.9 (resp. 0.7) higher of the total CO_2 embodied emissions. One can also notice that the importance of the space heating demand is greatly decreasing in the rebuild project seen that the embodied impacts become greater. The total energy demand related to heating, cooling and (building and user) electricity is, in both cases, the most harmful contribution to both impacts. For the *retrofit* (respectively *rebuild*) project, the space heating demand represents 42.2% (resp. 38.3%), the space cooling 19.8% (resp. 21.4%) (due to the quite high solar gains) and the electricity 37.9% (resp. 40.3%). These percentages clearly show that both buildings have very similar thermal behaviours. In conclusion, seen that (1) most papers dealing with LCA applied to buildings highlight the major impact of the use phase on the total life-cycle impact; and (2) the main purpose of this paper is to highlight the impact of the construction and demolition site operations of the building; no further details about the use phase are presently provided.

5.2 LCA without the use phase: *retrofit* versus *rebuild*

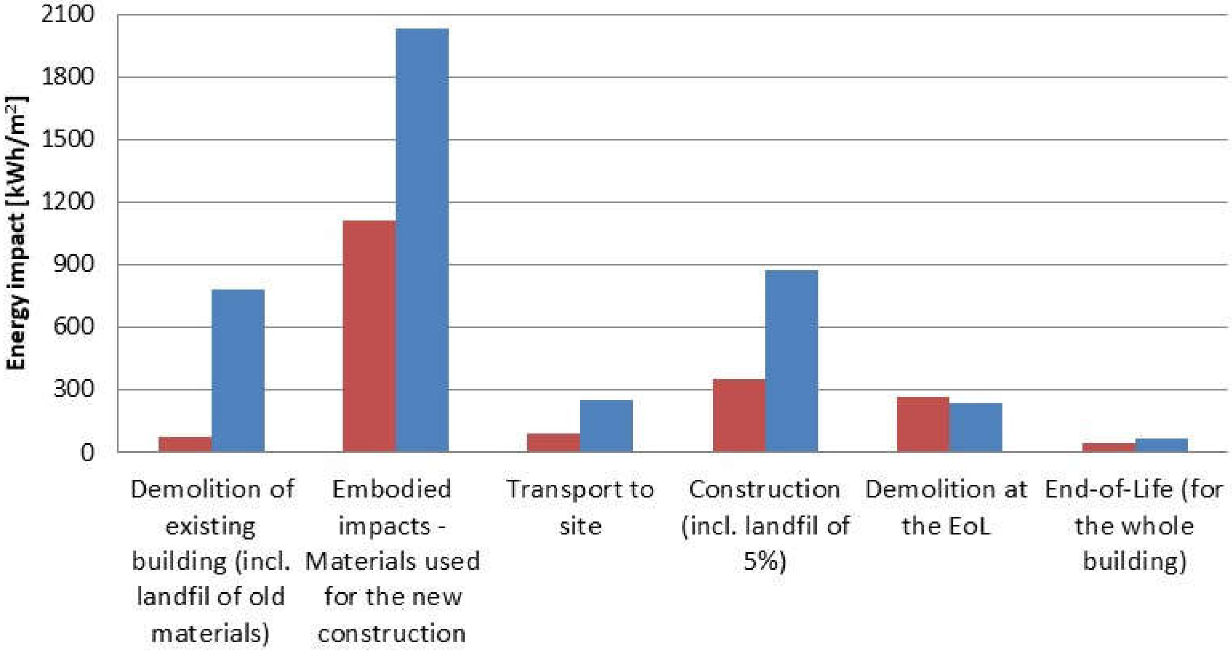

Figure 2: Energy impact [kWh/m^2] per phase, respectively for the *retrofit* project (red bars) and for the *rebuild* project (blue bars) (use phase is excluded)

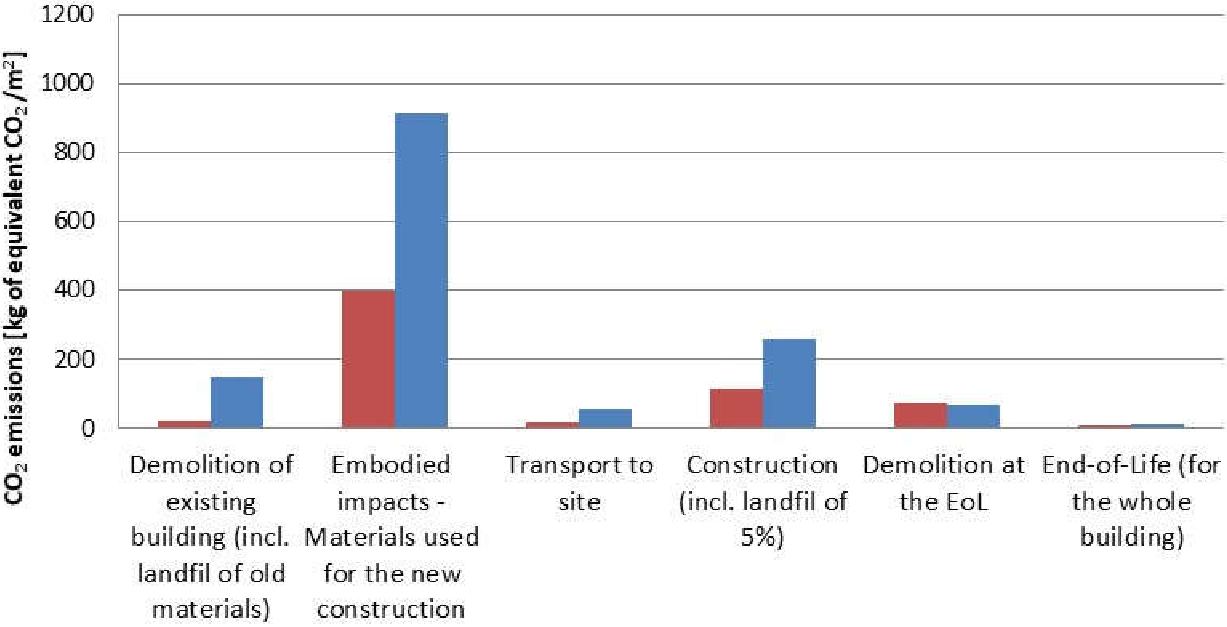

Figure 3: CO_2 emissions [kg of equivalent CO_2 /m^2] per phase, respectively for the *retrofit* project (red bars) and for the *rebuild* project (blue bars) (use phase is excluded)

For both projects, the embodied impact (material used for renovation in the *retrofit* project and material used to rebuild the building in the *rebuild* project) represents the highest impact (as far as energy and CO_2 emissions are concerned). The second most harmful phase, in both cases, is the construction phase. The demolition phase is however taking a quite important part in the balance in the case of the *rebuild* project. If the impacts of the demolition of the existing building and of the demolition at the end of the life are summed, the demolition phase indeed becomes the second most harmful phase in the case of *rebuild* project. In the *retrofit* project, the demolition of the existing building represents a small part of the impact seen that the major parts of the building are being kept as is.

In order to compare the differences between the retrofit and the rebuild project, the relative difference (in %) between both impacts is presented in Table 6 for each phase.

Table 6: Relative difference in % between the *retrofit* and the *rebuild* project.

	Energy	GWP
Demolition of roof and finishing (incl. landfill of old materials)	90.8%	86.4%
Embodied impacts - Materials used for retrofit or rebuild	45.5%	56.3%
Transport to site	65.0%	65.0%
Construction (incl. landfill of 5%)	59.6%	55.8%
Demolition at the End of life	-11.5%	-7.2%
Landfill at the End of life (for the whole building)	30.6%	44.9%
Total (without use phase)	54.5%	56.6%

Overall, the impacts of the *retrofit* project only represent 54.5% of the *rebuild* project in terms of energy and 56.6% in terms of CO_2 emissions. Except for the demolition impacts at the end of the life of the buidling, both indicators are always significantly lower for the case of renovation. The major part of the difference between the two scenarios can be attributed to the demolition of the existing building, the construction phases, the materials embodied impacts. But the demolition phase is undeniably the main contributor to the difference between the two scenarios, before the construction and transportation phases.

The considered building presents a high patrimonial value, and hence some specific works had to be performed to maintain the architectural aspect of the main facades. Therefore, the aforementioned results, clearly in favour of the retrofit project, should even be more significant for "more traditional" buildings. Without this architectural value to be preserved, the building could have been insulated by the outside reducing even more the impact of the demolition phase of the retrofit scenario.

6. Conclusion

In this paper, in order to feed the debate about the environmental soundness of demolition/ reconstruction of building vs. refurbishment, one LCA tool developed in a previous research to study two environmental impacts over the life cycle of buildings, under different climates, was updated. The updated tool allows taking into account (1) the demolition phase, (2) the construction phase and (3) the impact of construction works (including the transportation of workers and materials). The tool was then used to compare the retrofitting of a public building built in Brussels in 1934 with its complete demolition and reconstruction, through two environmental impacts, the global warming potential and the energy consumption.

Firstly, it is concluded that the use phase is the most harmful phase in both cases. Secondly, the impacts related to the demolition and construction phases together with the material embodied impacts are found to have a significant weight in the balance. For the selected case study, and considering that the same thermal performances were reached in both cases (as evidenced using the LCA tool), it was concluded that the retrofitting of the building is significantly less harmful than its complete demolition / reconstruction.

In addition to the environmental concern, others important aspects – such as the patrimonial value of the building, the social problems associated to demolition (especially when the demolition of dwellings is concerned) or the costs – should also be carefully assessed in each specific case. The tool updated in this paper and the results of its application to a public office building in Brussels are useful to support the development of policies in favour of the retrofitting of the existing building stock and to highlight to importance of including the whole life cycle of the building in the analysis.

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Appendix 1 – picture of the building before refurbishment (A2M, 2011)

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Appendix 2 : Picture of the retrofitted building (A2M 2011).

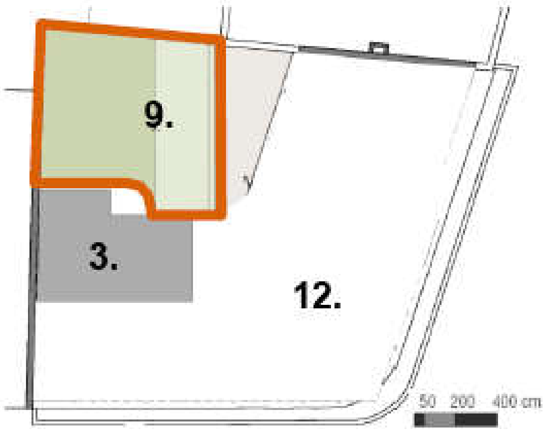
Appendix 3 : Plans and section of the retrofitted building (adapted from A2M (2011)): 1. Meeting room, 2. Sanitary block, 3. Technical room, 4. Kitchen, 5. Courtyard, 6. Archives, 7. Entrance, 8. Office room, 9. Void, 10. Fire escape, 11. Green roof, 12. Roof

Basement floor

Ground floor

First floor

Second floor



Technical room on the roof

Cross section (Vanpé Street)