GIS-based Life Cycle Assessment of urban building stocks retrofitting

A bottom-up framework applied to Luxembourg

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Abstract— *The building sector represents one of the major sources of environmental impact due especially to space and domestic hot water heating and construction works. A number of studies focused so far on estimating the energy savings and carbon emissions reduction potential achievable by retrofitting urban building stocks, nevertheless a shift to life cycle assessment is needed to properly assess the environmental impacts in a more holistic way.*

The aim of this study is to develop a geospatial data model for the life cycle assessment of environmental impacts of building stocks at the urban scale. The methodology includes: geospatial processing of building-related data to characterize urban building stocks; a spatio-temporal database to store and manage data; life cycle assessment to estimate potential environmental impacts.

The methodology was tested for a case study in Luxembourg and preliminary results regarding the retrofitting stage of residential buildings were provided for one entire city. The data model is part of a wider bottom-up framework being developed to support decision about building stock retrofitting for sustainable urban planning.

Keywords— Urban building stocks; Retrofitting; Life Cycle Assessment; Spatio-temporal database; Geographical Information Systems.

I. INTRODUCTION

The building sector represents one of the major sources of environmental impact in Europe, mainly due to space heating, domestic hot water heating and construction works [1]. In the European Union the 2010/31/EU [2] and 2012/27/EU [3] Directives contributed to the creation of a wide legislative framework for the reduction of energy consumption of buildings. In this respect, public authorities play a fundamental role in designing and implementing sustainable plans, for which a reliable estimation of the current state of the building stock is needed.

Many studies focused on the development of building stock energy models using a range of bottom-up approaches [4] to estimate the energy demand of large building settlements and their energy saving potential achievable by the implementation of retrofitting measures. Whilst major environmental impacts of buildings depend on the use of energy in their operational stage, the transition to low-energy and nearly-zero energy buildings determines an increased importance of the construction and retrofitting stage. As a consequence, a shift towards a life cycle approach for urban building stocks has been suggested by many authors (e.g. see [5]) to evaluate the environmental improvement potential in a more holistic way.

Life Cycle Assessment (LCA) has been widely applied to evaluate the environmental impact of buildings [6-9]. Three main stages can be distinguished in their life cycle [10]: product stage and construction process; use stage; end-of-life stage. The effect of retrofitting buildings in a life-cycle perspective has been investigated by many authors for single buildings [11]. However, the evaluation of building retrofitting at urban or larger scales has been rarely shaped in a LCA framework, especially due to methodological hurdles and data availability problems. Omitting the embodied energy and greenhouse gases emissions of retrofitting could lead to potential overestimation of the environmental benefits and over-representing their energy-savings contribution [12].

Few recent studies focused on the LCA of large building stocks using a bottom-up approach. Analyses were carried out at different scales, from the urban scale [13,14] to the national [12,15,16] and transnational scale [17]. The *archetypes technique* [4], originally conceived for building stock energy analysis and successively extended to LCA is commonly used in studies of this kind. This method consists in modelling a number of buildings representative of the stock, simulating their environmental performance and then extrapolating the results to the entire building stock. Results delivered include estimation of the environmental improvement potential of building stocks achievable by implementing retrofitting measures [16,17], testing of sustainable energy targets for buildings [13,15] and optimization of the energy supply [14]. One of the limitations in the *archetypes* approach is the obvious simplification, which does not allow an accurate description of the full variety of geometrical and construction characteristics of buildings.

Geographical Information Systems (GIS) offer the opportunity to manage and automatically process information at larger scales taking into account the spatial dimension and achieving a higher level of detail. The development of spatial databases could support LCA at the territorial scale and significantly contribute to the reduction of work time to perform the LCA study [18]. The integration of GIS in large scale LCA studies is particularly promising [19]: to localise impact sources and provide spatialized input data; develop spatialized inventory models; visualise results for stakeholders. A coupling between LCA and GIS has been suggested in several fields, however consensus is still missing on the way they should be integrated and methodological advancements are further needed [20].

The goal of this study is to develop a geospatial data model for the life cycle environmental impact assessment of building stocks retrofitting at the urban scale. The adopted approach aims at advancing the building stock modelling from a pure *archetypes technique* towards a *building-by-building technique* by the intensive use of geospatial data and a spatio-temporal database. The operational objectives of this study are:

1) to characterise the residential building stock of one entire city by developing and applying automated algorithms to extract information from georeferenced building topologies, identifying materials and components of buildings and developing a spatio-temporal database to handle data;

2) to perform a preliminary environmental assessment of the retrofitting stage of residential buildings for an entire city based on a coupling between LCA and GIS. The environmental assessment was initially limited to the retrofitting stage and will be extended to other stages of buildings' life cycle in a future step to provide results relevant for planning retrofitting actions on buildings.

The residential stock of the city of Esch-sur-Alzette (Luxembourg) was selected as a case study to test the methodology. The geospatial data model is part of a wider bottom-up framework being developed for decision support on building stock retrofitting in sustainable urban planning.

II. Materials and Methods

The methodology includes the following steps: characterisation of the building stock using georeferenced data, geospatial processing and analysis methods and development of a spatio-temporal database to store and manage data; preliminary LCA of the building stock retrofitting stage. The dataset, methodology and case study are detailed in this section.

A. Data requirements

The minimum data requirements to apply the methodology are a georeferenced Digital Surface Model (DSM) and a Digital Terrain Model (DTM) as well as georeferenced building footprints and attached attributes on building characteristics.

The DSM and DTM are derived from LiDAR data and represent respectively the elevation of the Earth's surface including all objects on it (e.g. buildings and vegetation) and the elevation of the bare ground surface only. The resolution has to be high enough to detect building roof patches. The building footprints should be available as georeferenced polygons. One polygon should correspond to one single building. Attached attributes should include at least the period of construction and the type of building (e.g. single-family or multi-family house).

To complement the geospatial data, information from other sources is required for the characterisation of materials and building components, such as technical standards for buildings, national and local regulations, statistical data, building libraries and interviews with construction experts.

B. Characterization of the building stock

The characterisation of the residential building stock was carried out in two main steps: gathering geometric information on single buildings across the city by automated geo-processing of spatial data; identifying the characteristic materials and components for buildings and their distribution in the stock, depending on the building type and period of construction.

1) Geoprocessing of building geometry

The main geometry-related data for single georeferenced buildings are systematically determined based on the combined use of DSM, DTM and building footprints vector file. Specific algorithms for geo-processing and analysis of data were developed using the software GRASS GIS [21].

The average ground level and roof elevation are attributed to every building by first intersecting the building footprint polygons respectively with the DSM and DTM, then by calculating the average elevation within every polygon. The average building height is subsequently computed and the building gross volume calculated by multiplying the building footprint by the average height.

The standard reference area defined by the German standard DIN 4108-2: 2011 [22] was selected as a proxy for the heated floor area of buildings and it is computed using the following formula: $A_N = V \cdot 0.32 \cdot (1/m)$, where A_N is the standard reference area in m^2 and V is the building gross volume in m^3. The ground floor and roof surface are also estimated based on the building footprint area.

Spatial data allow the computation of the wall surface delimiting the building envelope, either external or in common with adjacent buildings. First, a boundary analysis is performed based on the building footprints to distinguish the parts of the building perimeter facing the outdoor and the parts in common with other buildings. Then, the length of each part is computed and multiplied by the height of the building to obtain the surface of walls. The number of adjacent buildings was also computed developing and using a specific algorithm to further identify the type of housing and distinguish detached houses to row-houses. The surface of internal walls, both load bearing and partition walls, is estimated based on the floor surface using the results of another study [17].

The "surface area to volume ratio" S/V given by the ratio between the envelope surface and the gross volume is finally calculated using the values estimated, in order to have information on the compactness of the buildings.

2) Characterization of building materials and components

The selection and classification of building elements to be modelled (Table 1) was made by adapting similar classifications from other studies and relevant standards [23].

A series of building elements representative for the building stocks are identified depending on the housing type and period of construction. For every building element the composition of materials and their thickness should be determined. The distribution of different building elements and components among buildings belonging to the same type and period of construction should then be defined based on statistics and experts knowledge. The share of renovated buildings in the stock can be estimated based on the list of granted construction and renovation authorisation provided by the municipality, on the expected service life of building components and on information provided by local experts.

Retrofit measures suitable for building envelope components are assumed according to legal requirements, standards and construction practice depending on the scope of the assessment.

Table 1 – Classification for building elements

Group	Building element
Substructure	Foundations
	Basement walls
Envelope	Roof
	Exterior walls
	Windows / Doors
	Ground floor
Interiors	Partitions
	Internal floors

3) Spatio-temporal database for data handling

A relational spatio-temporal database was developed to handle building-related data at the city scale using PostgreSQL [24] and its extension PostGIS [25] for geospatial data (Fig. 1). The structure of the data model consists of several levels according to the standard EN 15643-2:2011 [10]: building, building part, element-component and product.

The *building* table corresponds to the georeferenced vector file of building footprints. Information about the year of construction and type of housing are stored at this level.

The *building part* level is used to link generic building elements and components to buildings. One record corresponds to one combination building – component/element. Information stored at this level includes the surface area of each component or element installed in a specific building, tilt, exposition (outer, inner, etc.) and year of construction/replacement.

The *element/component* level includes generic building elements as defined in Table 1. Two distinct tables are foreseen for opaque and transparent elements.

The *product* level contains information regarding materials composing generic building elements and information regarding glazing and framing for generic transparent components. Three distinct tables are used to store the data, respectively materials for opaque building elements, glazing and framing. Material properties such as density, conductivity and expected lifetime are stored at this level. For glazing and framing, the type, U-value and thickness are recorded. As the relationship between opaque building elements and materials is of the *many to many* type, an additional table is necessary to link the two. In this table the thickness of the several layers of materials composing the element and their order is specified.

The database is used to automatically associate elements and components to real buildings. In case information about materials, building elements and their state of renovation is not available for individual buildings, these can be randomly attributed among buildings in the stock based on the distributions defined above and depending on the type of housing and period of construction. Specific queries have been defined for this task.

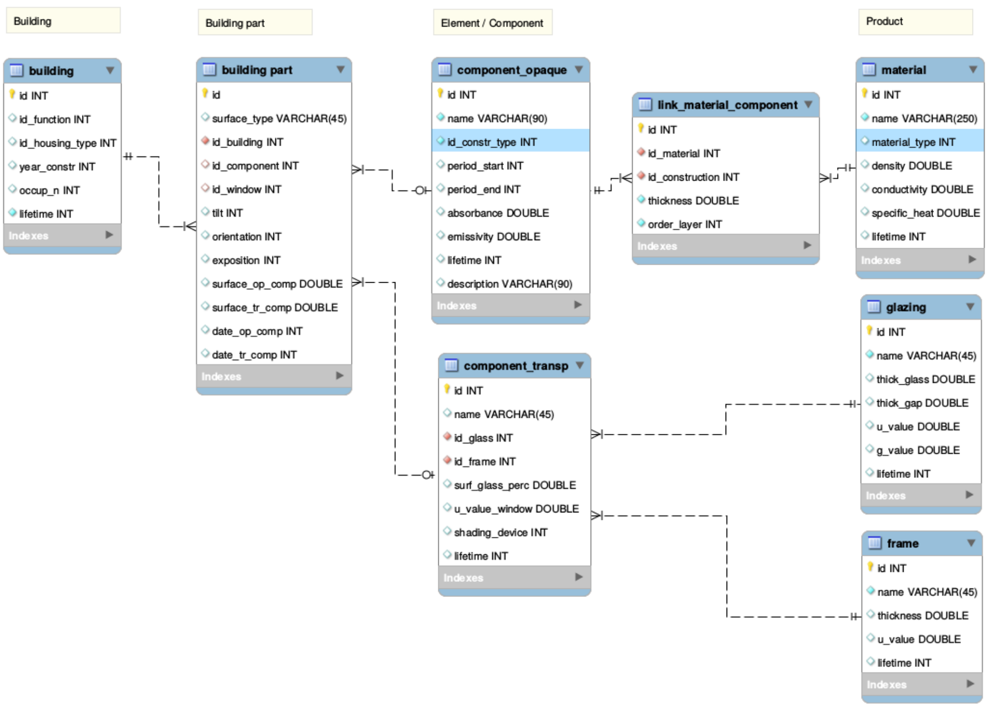

Fig. 1 Diagram of the database model for building stocks.

C. Life cycle assessment of retrofitting

A preliminary LCA assessment of buildings at the urban scale was carried out to quantify the environmental impact of implementing retrofitting measures according to the EN 15643-2:2011 and EN 15978:2011 standards [26]. The software SimaPro 7.3.3 [27] and the database Ecoinvent 2.2 [28] were used at this aim.

The effect of retrofitting was assessed by simulating the implementation of measures consistent with every period of construction and type of building, namely insulation of external walls, roofs and ground floors according to relevant standards and regulation requirements. The evaluation of the lifecycle impacts was performed using the method CML 2 baseline 2000 [29] for the reference building materials and components defined above. Six indicators were selected according to EN 15643-2:2011 [10]: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (OPD), Photochemical Ozone Creation Potential (POCP). The indicator GWP was selected to show results in this paper because: 1) it is relevant for the construction sector [9]; 2) it makes results comparable with other studies at large scale, which mostly use GWP as impact category.

The normalisation step brings all calculated indicators to be expressed by the same measuring unit (average inhabitant equivalent) and thus allows comparing results for different impact categories. Despite normalization is apparently value-free, it should remembered that it implicitly introduces weighting between categories, Indeed, the ones for which the total contribution of western Europe activities is higher will automatically receive a lower normalized value and therefore will be less important in the comparison. The normalised results were introduced in the city database and then extrapolated to the whole building stock. Georeferenced maps were produced to visualise the sources of impact across the city and communicate results to stakeholders.

D. Assumptions and limitations

Assumptions and limitations of this study were carefully evaluated and are reported in this section. With regard to the characterization of the building stock, geospatial data and analysis are used to have detailed information for buildings across the city. However, some approximations and simplifications concerning the geometry and components of buildings are unavoidable at the urban scale. The average height of buildings is computed and used to estimate the extension of external walls. Similarly, the surface of internal floors is evaluated based on the building footprints. Buildings with complex geometries might be affected by simplifications of this kind. The distribution of building materials, components and the state of renovation is assumed based on statistical data, building libraries and other datasets. Verification of the actual state of the building stock against empirical data from a sample of buildings will be addressed in a future step. Service life of buildings is assumed for every type of building and period of construction based on reference values.

The potential impact of retrofitting is currently evaluated only at the level of the production of retrofits materials and components. The transportation, construction works and material disposal due to retrofitting are neglected at this stage but will be included in a future step of the research. Nevertheless, other studies [30] demonstrated that construction works and disposal might be neglected as they constitute a minor part of the environmental impact of buildings.

E. Case study

The city of Esch-sur-Alzette (Luxembourg) was selected as a case study to test the methodology. The city counted a population of 31’898 inhabitants and a total of about 13’000 housing units in 2013. The following housing types were identified, in line with other studies for Luxembourg [31]: single family houses (SFH), row-houses (RH), multi-family houses (MFH). Geospatial data were provided by the Municipality, including DSM and DTM at a spatial resolution of 1 m and georeferenced building footprints (Fig. 2).

a.  b. 

Fig. 2 Spatial data for Esch-sur-Alzette: a. DSM; b. building footprint vector data.

Data about material density and thermal properties were obtained from the standard DIN 4108-4:2013 [32]. Information about the expected lifetime of materials was extracted from technical documents [33] and other studies [17]. A series of building elements were identified based on the common construction practice in Luxembourg (Appendix 1) and recorded in the database. Information about building envelope components and technical systems for buildings were obtained from technical standards, national regulations [34], statistics, building libraries for Luxembourg and neighbouring countries with similar building stock characteristics [35], previous studies [17,36] and advice from local experts.

Table 2 – Distribution of opaque envelope components among residential buildings in Esch-sur-Alzette based on the period of construction.

Period	Structure (n.buildings)	Walls (n.buildings)	Roof (n.buildings)	Floors (n.buildings)
< 1948	Masonry (3445)	Stone (2412) Brick (1033)	Wood (3445)	Wood (3445)
1949-68	Masonry (1218) Concrete (368)	Brick (317) Slag bl. (952) Conc.bl. (317)	Wood (1339) Conc. (247)	Wood (476) Concrete (1110)
1969-94	Masonry (453) Concrete (280)	Brick (73) Slag bl. (440) Conc.bl. (220)	Wood (554) Conc. (179)	Concrete (733)
>1995	Masonry (288) Concrete (240)	Brick (82) Slag bl. (298) Conc.bl. (148)	Wood (338) Conc. (101)	Concrete (439)

Retrofitting measures were defined for the building envelope elements modelled. National legal requirement binding the maximum U-value for building envelope components [34] were assumed to size the retrofitting measures (see Appendix 1). The building elements were then distributed across the building stock based on the period of construction and housing type (Table 2).

III. Results

A. Characterization of the building stock

The main geometrical features of buildings in Esch-sur-Alzette were estimated by analysing and processing the geospatial data available. The heated floor surface was computed for all residential buildings and aggregated at the city scale per type of building and period of construction (Fig. 3). SFH represents a small part of the stock (1.9%), while RH and MFH represent respectively 42.7% and 55.4% in terms of floor surface. Buildings raised before the year 1949 constitute 47.5% of the floor surface.

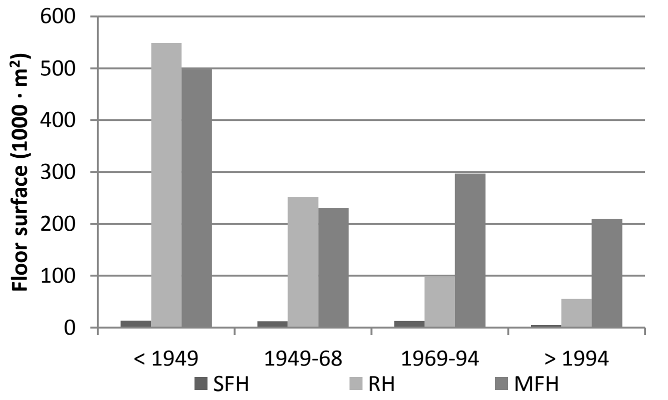

Fig.3 Total floor surface of residential buildings in Esch-sur-Alzette per type of housing and period of construction.

Fig. 4 shows the distribution of ranges of the surface area to volume ratio S/V of residential buildings for the city of Esch-sur-Alzette depending respectively on the type of housing and period of construction. The median S/V resulted 0.65 for SFH, 0.49 for RH and 0.38 for MFH suggesting that there is a remarkable difference in the compactness of different housing types. Different periods of construction are also denoted by different S/V values, being generally higher for the period 1949-68 (median: 0.50) and lower for the periods before 1949 (median: 0.45) and after 1994 (median: 0.42).

The database made it possible associating construction materials and components to residential buildings and further characterizing the stock of material across the city. Fig. 5 shows the estimated total amount of material in residential buildings based on the year of construction. It is possible to link the use of construction materials to the economic development of Esch-sur-Alzette, i.e. construction emerged at the beginning of the 20th century when the mining for iron in the vicinity was at its peak and new steel mills were installed. The city did not suffer important destructions during the world wars but the construction of new buildings decreased to near zero although the mining and the production of steel remained high. The post-wars constructions recovered the war gap and then became stable following the increase in population and in steel producing capacity until the 70's when the construction reduced progressively. A significant stagnation point can be observed in the 80's, when several restrictive conditions concurred: the full closing of the mines, the oil crisis, the decrease and then the complete stop of high furnace steel production. The construction development resumed once this crisis over and is now relatively stable.

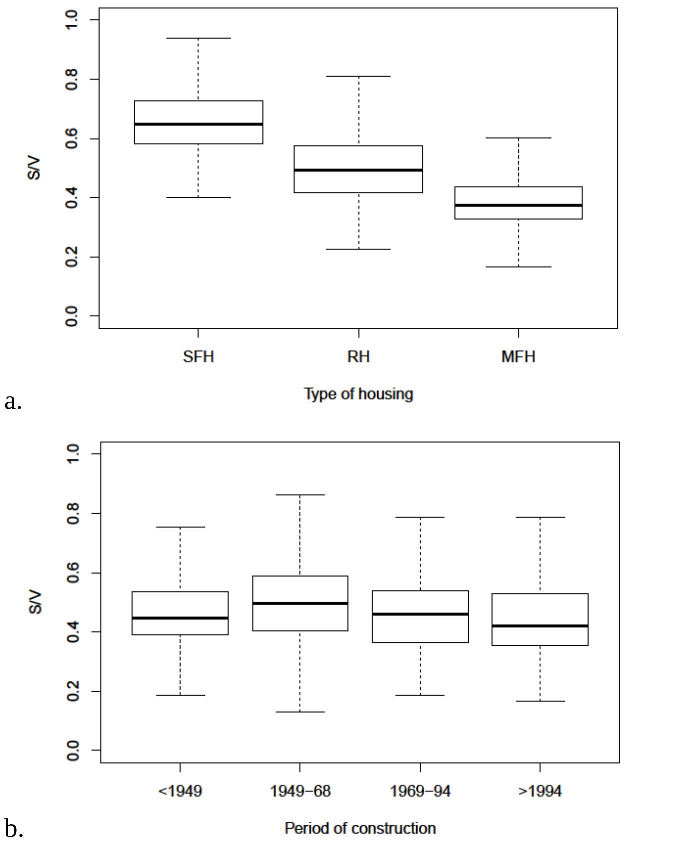

Fig. 4 Distribution of surface area to volume ratio (S/V) of residential buildings in Esch-sur-Alzette per type of housing (a) and per period of construction (b).

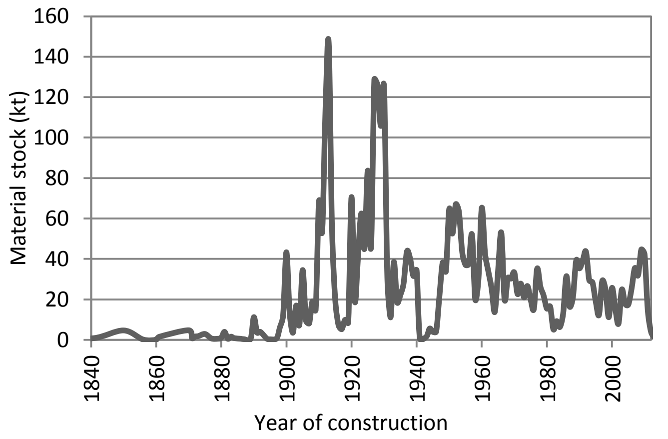

Fig. 5 The material stock over the time estimated for the residential buildings of Esch-sur-Alzette.

Results were aggregated at the city scale and average values were calculated to characterise residential buildings belonging to different housing types and periods of construction (Fig. 6). For SFH, the mass of materials per unit of heated floor surface is higher for envelope elements, especially external walls. For MFH, generally compact and taller, the internal elements such as partitions and floors account for greater mass of material in relation to their floor surface. RH are in an intermediate situation. The overall amount of material per unit floor surface is generally higher for MFH than for RH and SFH. Older buildings are generally characterised by a greater mass of materials due to massive structures for external walls.

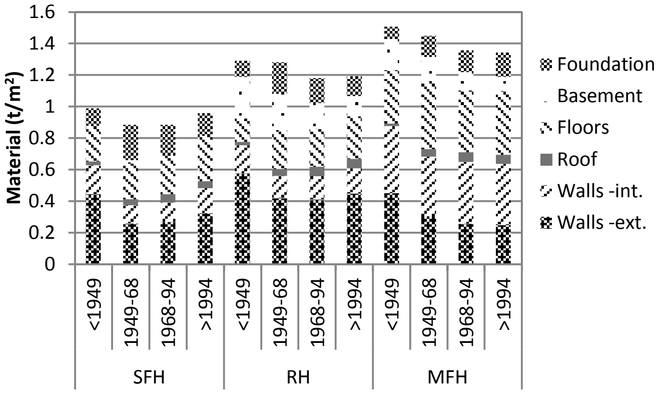

Fig. 6 Average mass of materials per square meter of floor surface for different housing types and period of construction of buildings in Esch-sur-Alzette.

B. Life cycle assessment of retrofitting

This section presents preliminary results of the life cycle assessment of retrofitting residential buildings in Esch-sur-Alzette. Results are provided for the addition of new material to the building envelope only. Benefits due to the reduction of energy use during the buildings use phase will be evaluated in a future step. Several scales were taken into consideration: component, building and city scale.

Results of GWP calculation per unit surface of single building components are shown in Fig.7. The impact associated with retrofitting is higher for concrete roofs and ground floors due to the materials to be replaced for this type of operation (e.g. tiles, cement screed). The impact of retrofitting older building components is higher due to the greater thickness of the insulation layer to be added to reach legal U-values.

Results of environmental impact calculation for single retrofitting measures were associated to buildings across the test case city based on their construction characteristics. Fig. 8 shows the average GWP per reference floor unit area of retrofitting residential buildings of different types and period of construction estimated from the whole housing stock. The influence of the building geometry on these results was analysed. Results demonstrated that the GWP associated with SFH retrofitting is higher than for RH and MFH. This effect depends on the compactness (cfr. Figs. 4 and 8), in particular, SFH have larger envelope surface per floor surface area to be retrofitted than the other building types. The impacts associated to wooden roofs retrofitting are reducing the average for roofs and therefore the ground floor stands out at the level of the city even if it is not the most important in Fig 7.

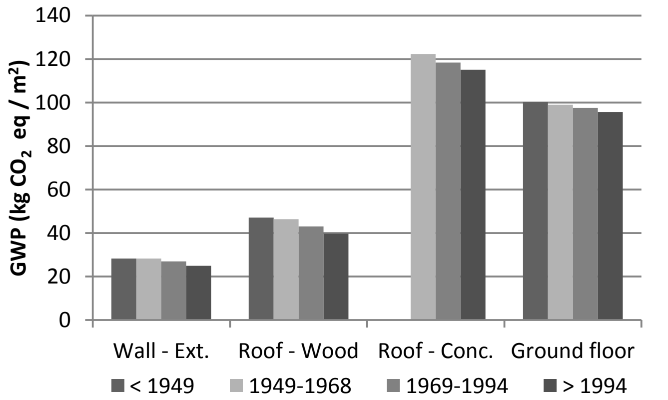

Fig. 7 GWP given by retrofitting per surface unit of several building components per period of construction in Esch-sur-Alzette: external walls, wooden roof, concrete roof and ground floor.

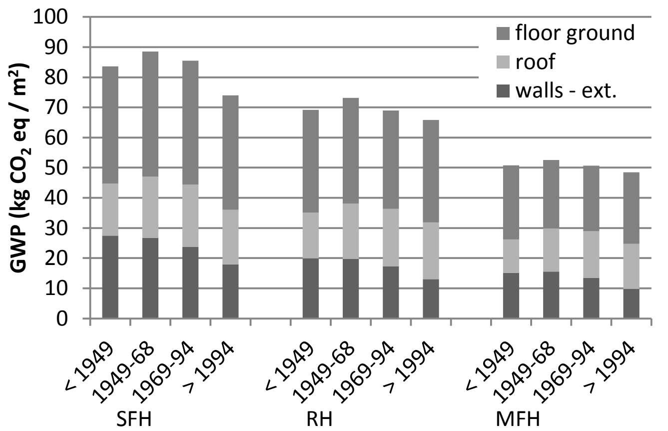

Fig. 8 Average GWP per unit of floor surface for retrofitting residential buildings of different type and period of construction in Esch-sur-Alzette.

Table 3 summarise results aggregated for the entire city. The total potential impact for retrofitting SFH across the city is far lower than other housing types due to their limited diffusion. Retrofitting the entire stock of RH and MFH would account respectively 66.66 and 62.33 kt CO_2 eq., namely 50% and 47% of the total impact. Among the different building elements, ground floors account for the highest GWP (63.14 kt CO_2 eq.), almost double the impact of retrofitting roofs (33.25 kt CO_2 eq.) and external walls (36.21 kt CO_2 eq.).

Table 3 – Floor surface and GWP for retrofitting the entire residential building stock of Esch-sur-Alzette.

Housing type	Floor surf. *($m^2 \cdot 10^3$)*	GWP for retrofitting *(kt CO_2 eq.)*			
		Gr. floor	Roof	Ext. walls	Total
SFH	42.8	1.72	0.82	1.07	3.61
RH	952.5	32.52	15.87	18.27	66.66
MFH	1235.0	28.89	16.56	16.88	62.33
Total	2230.3	63.14	33.25	36.21	132.60

A series of maps was finally produced to show the distribution of impacts due to retrofitting of buildings across the city of Esch-sur-Alzette. The map of GWP is shown as an example in Fig. 9. Impacts associated with building retrofitting are potentially higher in the once fortified area of the city centre (South –East) where buildings are mainly of type MFH, with a superior density to the rest of the city, older and of greater size. The suburbs are characterised mainly by RH of smaller size and therefore present lower potential impacts.

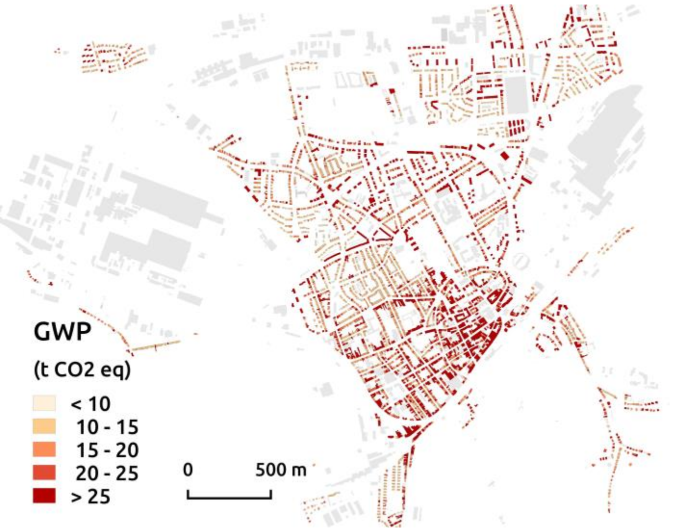

Fig. 9 Map of estimated GWP for retrofitting residential buildings in Esch-sur-Alzette (non-residential buildings displayed in grey).

Results of the life cycle impact assessment of retrofitting different building elements using the selected impact categories were normalised and aggregated at the city scale (Fig. 10). Four degrees of significance can be observed among the normalised results: highly important (ADP), important (GWP), relatively important (AP, EP), less important or negligible (POCP, ODP). From the construction and retrofit point of view POCP and ODP could be neglected, on the other hand POCP has a significant local impact in urban areas and should be considered in the perspective of including the heating consumption of buildings in the assessment.

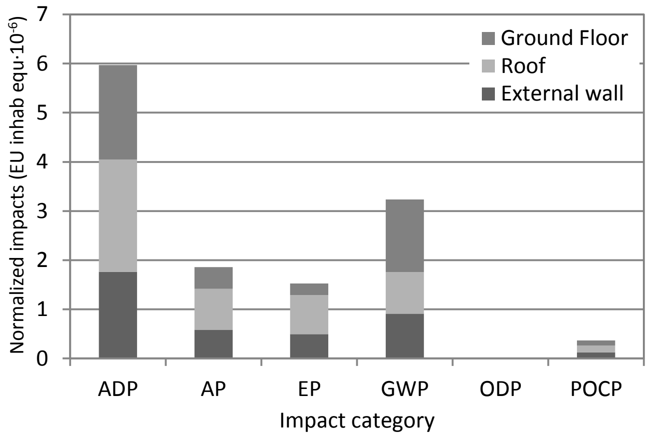

Fig. 10 Normalised impact results for retrofitting the residential building stock of Esch-sur-Alzette, grouped by impact categories and building elements.

IV. Discussion

The geospatial approach presented in this paper represents a substantial effort to advance the LCA of building stocks from pure *archetypes* to a *building-by-building* approach.

This approach offers a series of advantages in comparison to the common *archetypes* technique. Firstly, the geometry and building characteristics are computed building-by-building with far higher precision due to a georeferenced relational database, while keeping the computation process relatively light and relying on automated geospatial processing.

The spatial dimension is explicitly taken into account making it possible not only identifying the sources of impact but also evaluating their distribution across the city. Results can be visualised as maps to provide support for stakeholders, improve communication and geo-localise the hot spots. This framework is flexible enough for data update and application to other contexts, due to its generic approach relying on a minimal set of standard input data.

Some limitations of this approach were identified and will be tackled in a future step. Firstly, several assumptions on the current state of the building stock were made regarding materials, components and renovation state of buildings. An estimation of the residual service life of different types of buildings and building components is also needed to have a proper assessment of the life cycle. More detailed information owned by municipalities (e.g. construction and renovation authorisation) and statistical data will be taken into consideration to enhance the model. Moreover, uncertainty analysis would help to assess the sources of uncertainty at urban scale estimations.

Secondly, preliminary results were provided regarding the addition of new materials for retrofitting purpose only, nonetheless an extension to the other stages of the life cycle will be addressed in a future step to provide a global view on the impact of retrofitting plans. In particular, concerning the construction process, transports will be included by identifying and localising the major production sites for construction materials and components and the recurrent transport types. Distances to the building sites will be subsequently calculated using GIS to assess the related environmental impacts. Regarding the operational stage, energy consumption plays a major role and will be predicted for the current and renovated state of the building stock using a suitable energy model based on existing European standards. Finally, the end-of-life stage will be taken into account by considering current dismantling and demolition operations, in addition to alternative practices (e.g. reuse and recycling).

Thirdly, comparison of calculated results with empirical findings would help in validating and corroborating the methodology and allow for more robust conclusions. However, empirical data availability is currently limited. The analysis of a sample of buildings for which more detailed data about geometry, materials, components and measured energy consumption are available is envisaged to this end.

Overall, this study proved the suitability of the geospatial model to achieve a better insight on large urban building stocks for their life cycle environmental impact assessment.

V. CONCLUSIONS

A geospatial framework was developed for the life cycle assessment of urban building stocks in a life cycle perspective. The approach was tested on the case study of an entire city in the Grand Duchy of Luxembourg and showed promising results for the characterisation of urban building stocks and the assessment of environmental impacts due to retrofitting at the urban scale.

Geospatial data and analysis were used to gather information about building geometry and typology at the scale of one entire city. The spatio-temporal database developed allows a rational management of the building data and a rapid characterization of the building stock in time and space. An estimation of the material stock relative to residential buildings across the city was possible using the database and contributed to provide a deeper knowledge about the current state of the building stock.

Preliminary results were provided for the impact of retrofitting buildings across the city. The GWP per floor surface unit resulted higher for SFH than for RH and MFH. Nonetheless, the total potential impact for retrofitting RH and MFH amounts to respectively 50% and 47%, being SFH just a minor part of the building stock. Results were displayed as maps for policy decision support. Normalisation showed that the consumption of abiotic resources (ADP) is the most important potential environmental impact for the retrofit, more important than the Global Warming Potential (GWP). Future work should also include an ADP evaluation for the construction of different types of residential buildings and period of construction.

The results of this study will be used as a basis for defining renovation measures and priorities of residential buildings at the urban scale and simulating different scenarios to reach the environmental targets established by local authorities.

Further steps are envisaged to extend the methodology to all the stages of building life cycle and to apply it to other cities in Luxembourg and other European Countries. This approach is generic enough to be adapted and used for different contexts, provided that a minimum spatialized dataset and other relevant information about the building stock under investigation are available. The methodology will be further implemented in the web-based open-source platform iGUESS [37] to support decision making in sustainable urban planning.

LIST OF ABBREVIATIONS

ADP Abiotic Depletion Potential

AP Acidification Potential

DSM Digital Surface Model

DTM Digital Terrain Model

EP Eutrophication Potential

GIS Geographical Information System

GWP Global Warming Potential

LCA Life Cycle Assessment

MFH Multi-Family House

ODP Ozone Depletion Potential

POCP Photochemical Ozone Creation Potential

RH Row house

S/V Surface area-to-Volume ratio

SFH Single-Family House

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APPENDIX 1

List of building elements and retrofit operations associated.

Code	Type	Period	Composition current state[1,2] Material (Thickness cm)	U-value (W/m^2K)	Retrofitting operation assumed	U-value [3] retrofit
W_01_ST	Ext. wall - Stone	< 1949	1(1.5), 4 (45.0), 2(2.0)	1.7	9(10.0), 2 (2.0)	0.32
W_02_BR	Ext. wall - Brick	< 1968	1(1.5), 5(24.0), 2(2.0)	1.7	9(10.0), 2 (2.0)	0.32
W_03_SL	Ext. wall - Slag cement block	1949-68	1(1.5), 6(24.0), 2(2.0)	1.4	9(9.0), 2 (2.0)	0.32
W_04_CN	Ext. wall - Concrete block	1949-68	1(1.5), 7(24.0), 2(2.0)	1.4	9(9.0), 2 (2.0)	0.32
W_05_BR	Ext. wall - Brick	1969-94	1(1.5), 5(24.0), 9(2.6), 2(2.0)	0.8	9(8.0), 2 (2.0)	0.32
W_06_SL	Ext. wall - Slag cement block	1969-94	1(1.5), 6(24.0), 9(2.6), 2(2.0)	0.8	9(8.0), 2 (2.0)	0.32
W_07_CN	Ext. wall - Concrete block	1969-94	1(1.5), 7(24.0), 9(2.5), 2(2.0)	0.8	9(8.0), 2 (2.0)	0.32
W_08_BR	Ext. wall - Brick	> 1994	1(1.5), 5(24.0), 9(5.6), 2(2.0)	0.5	9(5.0), 2 (2.0)	0.32
W_09_SL	Ext. wall - Slag cement block	> 1994	1(1.5), 6(24.0), 9(5.6), 2(2.0)	0.5	9(5.0), 2 (2.0)	0.32
W_10_CN	Ext. wall - Concrete block	> 1994	1(1.5), 7(24.0), 9(5.5), 2(2.0)	0.5	9(5.0), 2 (2.0)	0.32
R_01_W	Roof - Wood	< 1919	10(3.0), 11(2.0), 16(0.5), 13(2.0)	2.6	9(14.0), 16(0.5), 13(2.0)	0.25
R_02_W	Roof - Wood	1919-68	10(3.0), 11(2.0), 9(1.5), 16(0.5), 13(2.0)	1.4	9(13.0), 16(0.5), 13(2.0)	0.25
R_03_W	Roof - Wood	1969-94	10(3.0), 11(2.0), 9(6.4), 16(0.5), 13(2.0)	0.5	9(8.0), 16(0.5), 13(2.0)	0.25
R_04_W	Roof - Wood	> 1994	10(3.0), 11(2.0), 9(11.7), 16(0.5), 13(2.0)	0.3	9(3.0), 16(0.5), 13(2.0)	0.25
R_01_CN	Roof - Concrete	1949-68	1(1.5), 7(16.0), 3(7.0), 16(0.5), 17(5.0)	2.1	9(14.0), 3(7.0), 16(0.5)	0.25
R_02_CN	Roof - Concrete	1969-94	1(1.5), 7(16.0), 9(6.4), 3(7.0), 16(0.5), 17(5.0)	0.5	9(8.0), 3(7.0), 16(0.5)	0.25
R_03_CN	Roof - Concrete	> 1994	1(1.5), 7(16.0), 9(11.7), 3(7.0), 16(0.5), 17(5.0)	0.3	9(3.0), 3(7.0), 16(0.5),	0.25
F_01_W	Ground floor	< 1949	9(3.0), 11(5.0), 3(10.0), 15(2.0)	1.0	9(13.0), 3(5.0), 15(2.0)	0.32
F_02_CN	Ground floor	1949-68	7(20.0), 3(10.0), 16(0.5), 15(2.0)	1.5	9(11.0), 3(5.0), 15(2.0)	0.32
F_03_CN	Ground floor	1969-94	7(20.0), 3(10.0), 9(2.8), 16(0.5), 15(2.0)	0.8	9(9.0), 3(5.0), 15(2.0)	0.32
F_04_CN	Ground floor	> 1994	7(20.0), 3(10.0), 9(8.1), 16(0.5), 15(2.0)	0.4	9(6.0), 3(5.0), 15(2.0)	0.32

Notes:

[1] Materials: **Plasters and renders:** 1-Lime mortar; 2-Gypsum plaster; 3-Cement screed; **Masonry and concrete:** 4-Calcareous stone; 5-Brick; 6-Slag cement block; 7-Concrete block; 8-Reinforced Concrete; **Insulation:** 9-Insulation mix; **Wood and boards:** 10-Wood (hard); 11-Wood board; 12-Gypsum fibre board; **Finishing, tiles and water-proofing:** 13- Roof tiles mix 1; 14 Roof tiles mix 2; 15-Floor tiles mix; 16-Bitumen; 17-Gravel.

[2] In lack of local data on building insulation, a mix of insulation materials was assumed from other studies [12]. The mix is composed as follows in terms of mass: Rock wool 36%, Glass wool 24%, EPS 28%, PUR 7%, XPS 5%.

[3] U-values for retrofit assumed from National requirements for Luxembourg [27] for external walls, external roof, ground floors over ground or basement.