A GIS-BASED APPROACH FOR THE ENERGY ANALYSIS AND LIFE CYCLE ASSESSMENT OF URBAN HOUSING STOCKS

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Abstract

Buildings are responsible for 40% of the final energy use and one third of greenhouse gas emissions in Europe. At the city scale, a quantitative assessment of the environmental impact of buildings is essential to support sustainable energy policies. Life Cycle Assessment (LCA) has been widely used to assess building related environmental impacts; however, its extension to the urban scale is still hampered by several operational challenges. Coupling LCA and Geographic Information Systems (GIS) has been identified as a promising solution but developments are still needed.

This paper presents an automated approach for the energy modelling and LCA of urban housing stocks based on GIS. The main steps of the approach are the following: (i) GIS-based building stock characterization; (ii) automated building-by-building energy analysis; (iii) Environmental impact calculation via LCA. The approach was applied to the test case city Esch-sur-Alzette (Luxembourg) to assess the potential environmental impact reduction driven by housing retrofitting.

Results were provided building-by-building and displayed as maps for improved communication. An energy savings potential of 35.3% and a Global Warming Potential (GWP) reduction of 30.8% were calculated as results of retrofitting. The average contribution of the retrofitting stage on the residual life of the building stock is 4 to 10% of the GWP, depending on the building type.

The study provided one of the first models able to perform a fully-fledged LCA of buildings at the urban scale in a bottom-up fashion. The results are meant to support local authorities in setting priority strategies for environmental impact reduction.

Keywords:

Building stocks; Retrofitting; Urban scale; Life Cycle Assessment; Geographical Information Systems

1 INTRODUCTION

Buildings are responsible for more than 40% of the global energy use and one third of greenhouse gas emissions in Europe [1]. The environmental impact of buildings has been identified as mainly due to space heating, domestic hot water and construction works [2].

Many studies focused on the assessment of the building energy demand and energy savings potential at the city scale [3,4], to support energy efficiency and carbon mitigation actions planning. However, most of them lacked a life cycle perspective that could lead to an overestimation of environmental gains for refurbishment options [5] due to the omission of other life cycle stages (e.g. production of building materials).

Life Cycle Assessment (LCA) is a largely used methodology to account for building related environmental impacts [6,7]. In recent times, interest started to arise around the LCA of buildings at the urban scale [8,9]. Integrating Geographic Information Systems (GIS) with building stock modelling has been identified as an effective way to provide a link between building statistics and spatial location of different building types [5]. Nevertheless, coupling LCA and GIS is still challenging due to several

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operational development needs [10], including software interoperability, data storage and processing, computation time reduction.

This paper presents an automated approach for the energy modelling and LCA of urban housing stocks based on GIS. The operational objectives are the following:

(i) Characterization of the housing stock of one entire city by GIS and statistical data collection, processing and storage in a spatio-temporal database
(ii) Energy analysis of the building stock running an automated building-by-building model
(iii) Environmental assessment of residential buildings retrofitting using LCA

The city of Esch-sur-Alzette (Luxembourg), counting about 13’000 housing units, was used as a case study to test the methodology.

2 DATA AND METHODS

2.1 Dataset

The main geospatial dataset was provided by the Municipality and includes laser scanner data (LiDAR) and building footprints data. A Digital Surface Model (DSM) and Digital Terrain Model (DTM) were generated from the LiDAR data to obtain information on the height of buildings. The building footprint vector file contains attributes such as the period of construction and the type of building (e.g. single-family or multi-family house).

In addition, complementary information is needed for the characterisation of materials and building components. Thermal properties of materials were obtained from the standard DIN 4108-4:2013 [11]. Lacking building libraries specific for Luxembourg, building envelope components and technical systems were characterised based on statistics, technical standards, regulations [12], building libraries for neighbouring countries [13] and previous studies [14,15] and interviews with local experts. A set of reference building elements and components and their share in the stock were consequently identified for every housing type and period of construction. U-values were maintained consistent with national reference values for existing buildings [16]. The current refurbishment state of the buildings was also taken into account by defining a share of refurbished buildings per period of construction according to the building permits register of the city complemented with national statistics information.

2.2 Building stock characterization

The characterisation of the residential building stock was carried out in two steps [14]. First, geometric characteristics (outer walls area, roof area, floor surface) were computed building-by-building across the city by automated geo-processing of the previously described spatial dataset in GRASS GIS [17]. Second, the reference building elements and components were distributed among real buildings based on their identified share in the stock and depending on housing type and period of construction. Retrofit operations were defined in accordance with the current national regulation requirements for the U-value of building envelope elements [12] and included: window replacement and insulation of outer walls, roof, and ground floor.

A spatial database was developed in PostgreSQL - PostGIS [18,19] to stock and process the collected data. Building elements and components, as well as retrofit operations, were associated to single buildings using specific queries in the database (see [14] for detailed description).

2.3 Energy analysis

The model for the energy analysis of the building stock is based on the national Luxembourg regulation for the energy performance of buildings [12]. The space heat demand is calculated on a monthly basis using equation (1):

$$Q_{h,M} = Q_{tl,M} + \eta_M \cdot (Q_{s,M} + Q_{i,M}) \quad (1)$$

where $Q_{h,M}$ is the monthly heat demand for space heating in *kWh*, $Q_{tl,M}$ is the monthly heat losses for ventilation and transmission in *kWh*, η_M is dimensionless heat gain utilisation factor, $Q_{s,M}$ and $Q_{i,M}$ are the monthly solar and internal heat gains in *kWh*. Simplifications for existing buildings were applied in accordance with the national methodology regarding thermal bridges, shading calculation, efficiency of heating and domestic hot water systems.

The model was implemented in a script in *R* [20] connected to the building database to automate the calculation for buildings across the city for the current state and after the implementation of retrofitting measures.

2.4 Life cycle assessment

A LCA of buildings retrofitting at the urban scale was carried out according to the standards EN 15643-2:2011 [21] and EN 15978:2011 [22] to quantify the environmental impact reduction potential. The software SimaPro 7.3.3 [23] was 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, as described above. The environmental impact of buildings was calculated for their residual life cycle respectively with and without the implementation of retrofitting measures. The analysis included the following life cycle stages:

- Retrofitting stage: production and transport of building material to be employed
- Operational stage: energy consumption for space heating and domestic hot water

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The functional unit selected is the entire housing stock in the city; the results calculated are then rescaled to 1 m^2 of floor surface. Residual service life of buildings was identified according to previous studies [15]. The foreground inventory data were obtained from the building stock characterization and the energy analysis, the background inventory data from the database Ecoinvent 2.2 [24].

The method CML 2 baseline 2000 [25] and a range of impact categories were selected for the evaluation of the lifecycle impacts according to EN 15643-2:2011 [21]: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (OPD) and 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 normalization step translates all the impacts belonging to different categories into the same metrics, i.e. the number of equivalent inhabitants that would generate those impacts. Normalization according to the method CML Europe West 1995 was carried out for direct comparison among impacts of different categories and identification of categories with the highest impacts. Some of the results are shown here in terms of GWP due to the importance of this impact category and for comparability with similar studies.

Results were produced for the expected residual service life and then expressed on a yearly basis and per floor area unit. An extrapolation to the entire building stock was finally performed by matching impacts with buildings across the city.

3 RESULTS

3.1 Energy analysis

Results of the energy need calculation for the residential buildings of Esch-sur-Alzette are shown in Fig. 1 per type of housing (Single-family detached houses SFH, Row-houses RH, Multi-family houses MFH) and period of construction (<1970, 1970-95, >1995). The energy intensity

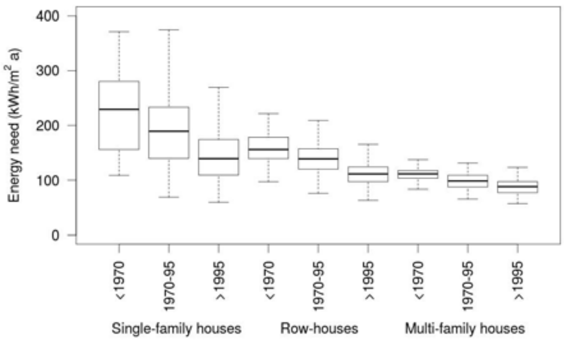

Fig. 1: Distribution of energy intensity for space heating and domestic hot water of residential buildings in Esch-sur-Alzette per type of building and period of construction.

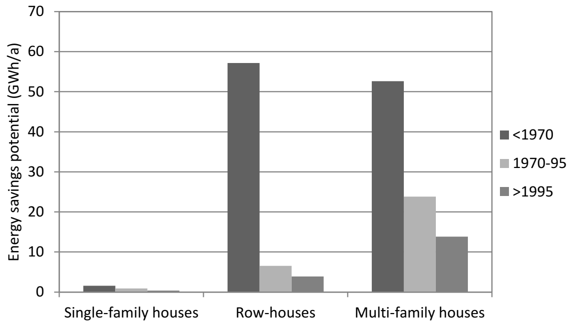

Fig. 2: Total energy savings potential after retrofitting residential buildings in Esch-sur-Alzette per type of building and period of construction.

per unit of floor area (*kWh/m²a*) highly depends on both period of construction and type of buildings, being higher for older buildings and for single family houses. The variability of energy needs within the same category of buildings is also highly dependent on the type of buildings. SFH have higher variability, due to a range of geometrical shapes resulting in different compactness of the building and different amount of heat losses.

The total energy need for space heating and domestic hot water of the housing stock calculated at the city scale in the current state amounts to 248.4 GWh/y. Results were validated against aggregated measured consumption data for natural gas provided by the local energy supply company. The comparison showed a good agreement, resulting in a difference within 10% between the calculated and measured consumption.

Results of the energy savings potential calculation at the city scale are shown in Fig.2 per housing type and period of construction. The highest energy savings potential is attributable to RH and MFH built before 1970, amounting to respectively 35.6% and 32.8% of the total. SFHs potential for retrofitting is the lowest due to their limited number. The energy savings potential for retrofitting the entire residential stock is 87.7

GWh/y, corresponding to 35.3% of the current energy consumption.

3.2 Life cycle assessment

This section presents the results of the LCA of residential building retrofitting across the city of Esch-sur-Alzette.

The average yearly GWP per floor surface unit was estimated for different types of housing and periods of construction without and with the implementation of retrofitting measures, taking into account the entire residual service life (Fig.3). A substantial GWP reduction is achievable by retrofitting buildings constructed before 1995. The GWP reduction potential is higher for older buildings (from 33% to 45% for buildings before 1970), due to the effect of building envelope insulation. For buildings after 1995 benefits are minor or even null after including the impact of the retrofitting stage. Looking at retrofitted buildings, the operational stage largely prevails over the retrofitting stage in a life cycle perspective. Nevertheless, the retrofitting stage accounts for 4% up to 10% of the GWP depending on the housing type.

Fig. 4 shows the results of the normalization step. Among the selected impact categories, ADP and GWP emerged as the ones with higher environmental impact while the others appeared as less important. The environmental impact reduction potential determined by retrofitting significantly differs among the considered impact categories. The average reduction potential is similar for ADP, GWP, and ODP (from 30.8% to 32.6%). The impact reduction potential is lower for AP and POCP, while an increase is observed for EP. At the same time, the impact categories with higher impact reduction potential are characterized by a lower contribution of the retrofitting stage to the total environmental impact, ranging from 6.5% for ADP to 8.6% for GWP. In contrast, the average contribution of the retrofitting stage to the total environmental impact is the highest for AP (35.1%) and EP (47.1%).

Results were finally aggregated at the city scale and displayed as maps for decision support. Fig.4 shows, as an example, the GWP reduction potential by retrofitting buildings at the district level. Greater GWP reduction potential was found for districts next to the city centre as a result of the interaction between urban density, housing type and geometry, age and refurbishment state of buildings. At the city scale, the total estimated yearly reduction potential is 18.3 kt CO_2 eq., corresponding to 30.8%.

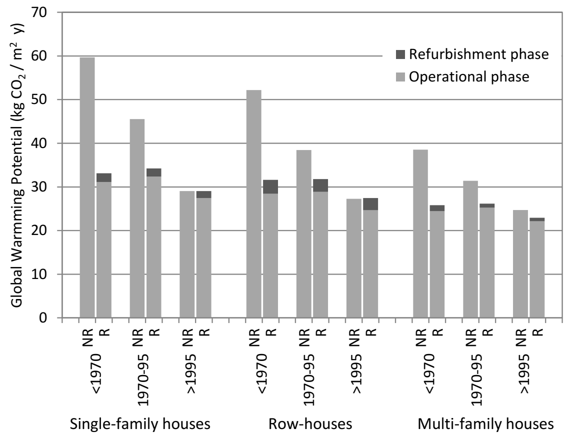

Fig. 3: Average GWP of residential buildings per floor area unit per type and period of construction without (NR) and with (R) implementing retrofitting measures in Esch-sur-Alzette.

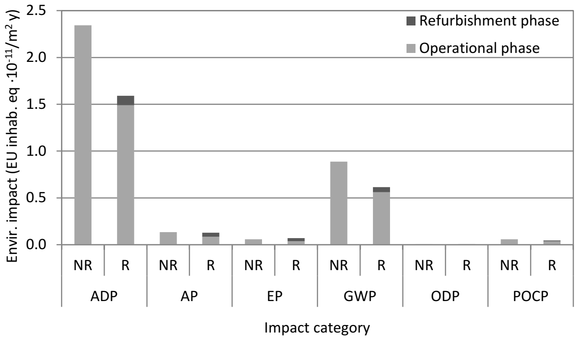

Fig. 4: Average normalized environmental impact of residential buildings per floor area unit without (NR) and with (R) implementing retrofitting measures in Esch-sur-Alzette.

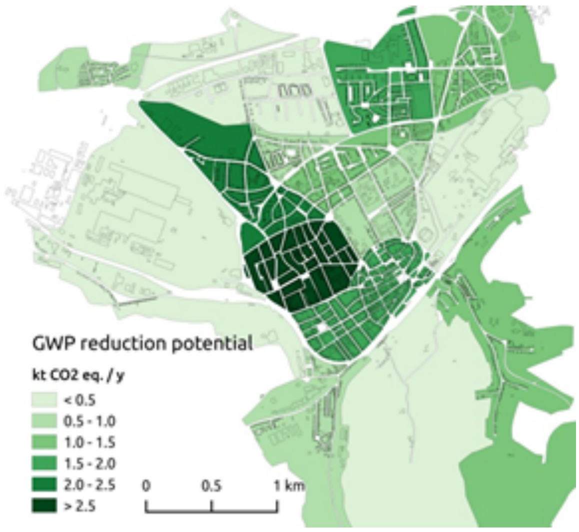

Fig. 5: Map of the GWP reduction potential of residential buildings in Esch-sur-Alzette after implementing retrofitting measures.

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4 DISCUSSION

This study provided one of the first efforts towards a fully-fledged LCA of buildings at the urban scale in a bottom-up fashion. The results are meant to support local authorities and city planners in setting priority strategies for energy savings and environmental impact reduction.

The approach is innovative compared to other commonly used approaches, e.g. *archetypes* [3,15], for the integration of GIS, energy modelling and LCA. GIS made it possible to take the geometry into account building-by-building with far higher precision and in a completely automated way. In particular, GIS processing provided an estimation of the area of outer building envelope elements such as walls and roof and to further distinguish walls in common between adjacent buildings from outer walls. The development of a spatio-temporal database allowed for the automatic delivery of input data for the energy and LCA models and their aggregation at the targeted level (building element/component, building, and city). In addition, the spatial dimension is explicitly taken into account and the framework is flexible for data update and application to other contexts.

However, the approach is affected by some limitations and assumptions. Developing a building stock LCA model at the urban scale is challenging for the number of buildings involved and the limited information available, especially regarding building materials, state of renovation, building usage and residual service life. As a consequence, several assumptions were made based on statistical data, national standards, regulations and previous studies. Uncertainty and sensitivity analysis will be addressed in a future step to study error propagation.

The study provided an estimation of the environmental impact reduction potential achievable by retrofitting the outer envelope of residential buildings across one city. This is to be considered as a theoretical figure as it does not include the actual rate of retrofitting implementation, nor cost-effectiveness aspects. The use of a simplified energy model in semi-steady state is justified as the study is limited to residential buildings and space heating demand evaluation. More complex dynamic models should be applied for the assessment of buildings with function other than residential and cooling demand estimation. Concerning the retrofitting stage, the disposal and waste treatment of existing building materials and components removed during the operations were currently neglected. Other stages of the buildings' life cycle, including the end-of-life stage, will be further included in a future step.

Another crucial point is results validation. Whilst we compared results of the energy consumption modelling in the current state against measured data, it is not completely possible validating results concerning energy savings potential and environmental impact of material production and retrofitting operations.

In spite of the additional work needed to provide more robust results, this study proved the effectiveness of the developed framework for the LCA of urban building stock and the evaluation of the effect of retrofitting.

5 CONCLUSIONS

A GIS-based LCA approach was developed to evaluate the environmental impact of urban building stocks and the reduction potential driven by retrofitting. The methodology was implemented and tested for an entire city in Luxembourg and provided promising results for the set up and development of building retrofitting scenarios.

Further developments will extend the evaluation to all the stages of building life cycle and to other cities in Luxembourg and other European countries. The models will be implemented in the web-based open-source platform iGUESS [26] to support decision in sustainable urban planning.

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7 REFERENCES

1. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

2. Tukker, A. et al., Environmental Impact of Products (EIPRO), Analysis of the life cycle environmental impacts related to the final consumption of the EU-25, in Technical Report EUR 22284 EN. 2006, European Commission, Joint Research Centre.

3. Swan, L. and Ugursal, V., Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 2009. 13, p.1819–35.

4. Kavgic, M. et al., A review of bottom-up building stock models for energy consumption in the residential sector. Building and Environment, 2010. 45(7), p.1683–97.

5. Österbring, M. et al., A methodology for spatial modelling of energy and resource use of buildings in urbanized areas. World Sustainable Building Conference WSB14. 2014, Barcelona, Spain.

6. Chau, C. K. et al., A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. Applied Energy, 2015. 143, p. 395–413.

7. Cabeza, L. F. et al., Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable Sustainable Energy Reviews, 2014. 29, p. 394–416.

8. Lotteau, M. et al., Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Building and Environment, 2015. 93, p.165–78.

9. Heeren, N. et al., A component based bottom-up building stock model for comprehensive environmental impact assessment and target control. Renewable and Sustainable Energy Reviews 2013. 20, p.45–56.

10. Geyer, R. et al., Coupling GIS and LCA for biodiversity assessments of land use. International Journal of Life Cycle Assessment, 2010. 15 (5) p. 454–67.

11. DIN, Wärmeschutz und Energie-Einsparung in Gebäuden - Teil 4: Wärme und feuchteschutztechnische Bemessungswerte, DIN 4108-4, 2013.

12. Règlement Grand-Ducal du 26 mai 2014. Performance énergétique des bâtiments d'habitation et fonctionnels. 2014, Luxembourg.

13. Loga, T. et al., Deutsche Gebäude-typologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden. 2011, Darmstadt.

14. Mastrucci, A., et al., GIS-based Life Cycle Assessment of urban building stocks retrofitting. A bottom-up framework applied to Luxembourg, in proceedings of EnviroInfo2015. 2015: Copenhagen, Denmark. p. 47-56.

15. Nemry, F., Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs. Energy and Buildings, 2010. 42, p. 976–84.

16. Ministère de l'Economie et du commerce extérieur, Leitfaden zur Verwendung von U-Wert-Typologien im Rahmen der Energie-passerstellung für bestehende Gebäude, v. 1.1. 2007, Luxembourg.

17. GRASS Development Team, Geographic Resources Analysis Support System (GRASS) Software. Open Source Geospatial Foundation Project. 2012. http://grass.osgeo.org

18. The PostgreSQL Global Development Group, PostgreSQL 9.4.0 Documentation. 1996-2014.

19. PostGIS 2.0 Manual – SVN Revision (14477) http://postgis.net/stuff/postgis-2.0.pdf (consulted: December 2015)

20. R Core Team, R: A language and environment for statistical computing. R Foundation for Statistical Computing. 2015, Vienna, Austria. URL https://www.R-project.org/

21. CEN, Sustainability of construction works – Assessment of buildings. Part 2: framework for the assessment of environmental performance, EN 15643-2, 2011.

22. CEN, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation Method, EN 15978, 2011.

23. PRé Consultants and Effting, S., Wizard Manual. Introduction into programming of Wizards in SimaPro 7. 2006. http://www.simapro.de/uploads/media/WizardManual.pdf

24. Ecoinvent Centre. Ecoinvent version 2.2 database.http://www.ecoinvent.org/database/ecoinvent-version-2/ecoinvent-version-2.html (consulted: December 2015)

25. Guinée, J.B. et al., Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. 2002, Dordrecht. Netherlands: Kluwer Academic Publishers.

26. De Sousa, L. et al., iGUESS – a web based system integrating urban energy planning and assessment modelling for multi-scale spatial decision making, in Proceedings International Environmental, Modelling and Software Society (iEMSs). 2012: Leipzig, Germany.

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