Life cycle assessment approaches applied to energy modelling of urban building stocks: a literature review

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Abstract

The buildings' sector is one of the major consumers of materials and energy in the world. Thus, the construction of more efficient buildings is a fundamental undertaking to reach a more sustainable future. The evaluation of energy demand during use is no more enough, urban policymakers and urban designers are asking for more broad evaluation scenarios for their aims. The life cycle assessment (LCA) approach coupled with the energy modelling of large building stocks could answer to this request. This paper analyses the main studies available in the literature that apply LCA to large building stocks. The research approach is usually performed in steps: the characterisation of the buildings, the energy modelling and the LCA study. In literature, very few studies performed a full LCA due to the high complexity considering large building stocks.

1. Introduction

In 2015, all 193 governments of the United Nations adopted the 2030 agenda for sustainable development comprehending its 17 Sustainable Development Goals (SDGs) (United Nations, 2015). Particularly, the SDG 11 "Sustainable cities and communities" emphasizes the importance of cities and in general, the settlements in which people live. According to the United Nations, from 2007, more than half of the world population is living in urban areas (around 55 %), and this percentage is foreseen to rise further (United Nations, 2018). Particularly, the building sector and its industry are great consumers in terms of energy and materials (Lotteau et al., 2015). By consequence, efficient buildings are fundamental to reach a more sustainable future maintaining high-quality life standards in cities. In this scenario, municipalities, mayors and cities councils are facing new challenges to improve sustainability in cities and need evaluation criteria and perspective, to establish the best solutions to decrease the overall environmental impacts (Mastrucci et al., 2017). The mere evaluation of energy demand during the use of buildings is no more enough. Nowadays, regulations (United Nations, 2015) and the scientific community ask to evaluate the implementation of different energy conservation measures, not only from the energy-efficiency point of view but considering a holistic approach, able to evaluate the real and complete environmental assessment of the proposed strategies. The Life Cycle Assessment (LCA) (ISO, 2006) approach may provide the answer to this request. The approaches employed in several studies found in the literature generally employ two steps to apply LCA to large building stocks. Firstly, the building stock is modelled, and the energy demand is assessed; secondly, the LCA is applied to the modelling inputs and outputs to assess the environmental impacts. This paper reviews the main studies available in the literature applying LCA to large building stocks (from neighbourhood to city scale). The results are summarized in Table 1 and explained in detail in the following sections.

Table 1: Review analysis results

	Reference	Norman et al., 2006	Li and Wang, 2009	Heeren et al., 2013	Stephan et al., 2013	Riera Pérez and Rey, 2013	Davila and Reinhart, 2013	Nichols and Kockelman, 2014	Trigaux et al., 2014	Anderson et al., 2015	De Wolf et al., 2017	Trigaux et al., 2017	Lavagna et al., 2018	Zhan et al., 2018	Sartori and Calmon, 2019
Buil. Stock	Region	Toronto, CND	Beijing, RC	Zurich, CH	Melbourne, AUS	Lausanne, CH	Cambridge, USA	Austin, USA	Belgium	Munich, D	Kuwait city, KWT	Belgium	Europe	Guangzhou, RC	Vitória, BR
	Aggregation[1]	A	A	A	A	B	A	A	B	A	A	A	A	B	A
	Energy modelling[2]	S-TD	S-TD	Pb-BU	Mixed statistical	T-TD	Pb-BU	T-TD	Pb-BU	Pb-BU	Pb-BU	Pb-BU	S-BU	T-TD	S-BU
Gaol and Scope	Goal[3]	1	1	2	2	1, 2	2	1	2	2	1, 2	1, 2	1	1	1, 2
	Functional Unit	inhabitant m^2/inhab	house	inhabitant	km^2 of neigh, inhabitant	m^2 of energy reference area	m^2 floor area	inhabitant	m^2 floor area	inhabitant	m^2 floor area	euro/m^2 total floor area	Inhabitant m^2 floor area	m^2 floor area	m^2 floor area
	Service life	50 years	NA	100 years	50 years	NA	varying	-	60	-	50 years	60 years	100 years	70 years	50 years
	Boundaries[4]	B, O, N, M	B, M	B	B, O, N, M	B, M	B	B, O, N, M	B, O	B, O, M	B	B, O	B	B	B
	LC Phases[5]	P, U	P, U, R, E	U	P, C, U	P, C, U	P, U, R, E	P, U	P, U, R, E	P, U, R, E	P, C, U	P, C, U	P,C,U,R,E	P, C, U	P, U
Inventory	Production/ materials Foreground data	Economic input-output model	Survey, statistical method	Archetypes characteristics	Statistical national averages	Statistics on local/ national database	Archetypes characteristics	Statistics on aggregated regional data	Archetypes characteristics	Archetypes characteristics	Archetypes characteristics	Archetypes characteristics	Statistics on European database, archetypes	Statistics on regional/ national databases	Statistics on regional database
	Databases Background data	Averaged public data	Survey and statistics	Survey and statistics	Survey and statistics	Statistics on local/ national database	Regional database	Statistics on regional data	Ecoinvent database	Ecoinvent, Okobau.dat	National inventories	Ecoinvent database	Ecoinvent database	Statistics on regional/national databases	Statistics on regional database
	Buildings use	Nationally averaged public dataset	Survey and statistics	Archetypes modelling + census data	Statistical modelling of archetypes	Statistics on local/ national database	Archetypes modelling	Statistics on regional data	Archetypes modelling	Archetypes modelling	Dynamic archetypes modelling	Archetypes modelling	Statistics on European databases	Statistics on regional/national databases	Statistics on regional database
	Mobility	Local database	Survey, Statistical method	-	Regional averages	Statistics on local data	-	Behavioural models + GIS based data	-	Surveys, statistics on regional database	-	-	-	-	-
Impact ass.	Impacts categories[6]	PE, GWP	GWP, PH, AD, EU, others	PE, GWP	PE, GWP	PE, GWP	PE	PE	OD, PH, AD, EU, others	GWP	GWP	LU	all ILCD impacts	Energy consumption, GWP	Operational Energy, CO_2 emis
	Normalization /weighting	-	✓	-	-	-	-	-	✓	✓	-	-	✓	-	-
	Uncertainty/ Sensitivity	-	-	-	✓	-	-	✓	-	✓	✓	-	-	-	-

[1] A = Archetypes, B = Building-by-building; [2] T-TD = Technical Top-Down, S-TD = Socio-econometric Top-Down, Pb-BU = Physics-based Bottom-Up, S-BU = Statistical Bottom-Up; [3] 1 = Evaluation of impacts at current state, 2 = Evaluation and comparison of future scenarios; [4] B = Buildings, O = Open spaces (places, streets, infrastructure), N = Energy Networks, M = Mobility; [5] P = Production, C = Construction, U = Use, R = Refurbishment, Maintenance, E = End-of-life; [6] GWP = Global Warming Potential, PE = Primary energy, PMF = Particle Matter Formation, PH = Photochemical Oxidation, AD = Abiotic depletion, EU = Eutrophication, LU = Land use

2. Building stock modelling methods

The aim of this step is the characterisation of the buildings in the large stock and its modelling to assess the energy use. This is a fundamental step to achieve reliable outputs from the LCA studies.

2.1. Building stock description methods

A fundamental and complex phase is the description of buildings at large-scale, called also building stock aggregation. Buildings need to be described starting from the individual stock features (building fabric, systems, usage patterns, etc.). This description relies on the availability of data, such as geographic information system (GIS), census data, building databases, etc. Buildings can be characterized by *archetypes* or with *building-by-building* methods. The *archetypes* method is used to create some "typical buildings" (from few to some thousands) that are able to well-characterize the entire building stock. Some up-scaling factors are then used to extrapolate results for all the building stock. The number of archetypes should be assessed considering the proper trade-off between simplification and representativeness (Lavagna et al. 2018). At smaller scales (neighbourhood or district), the number of archetypes is usually small due to a relative homogeneity. On the other hand, considering city scale (or regional, national), a higher number of archetypes is required to consider different building typologies, construction characteristics and climatic zones (Mastrucci et al., 2017). In the second method, *building-by-building*, each building is characterized individually based on real case studies, selected for their representativeness. The whole building stock may be evaluated by direct aggregation (summing-up) of results of individual buildings.

2.2. Energy modelling methods

The building stock energy modelling methods can be divided into two main approaches (Swan and Ugursal, 2009): *top-down* and *bottom-up*. *Top-down* models estimate the energy consumption of buildings from agglomerated data on large-scale. Usually, they do not need detailed data of the buildings, because they are able to (mainly statistically) estimate long-term relationships among the energy use of an urban area and some drivers. The typology of these drivers brings to a further differentiation among *top-down* models. They can be subdivided *in socio-econometric* (van Vuuren et al., 2009), *technical* (Norman et al., 2006) and *physical models* (Zhang, 2004). On the other hand, the *bottom-up* approaches combine the calculation of individual buildings (or small groups of buildings) to describe the city or the region. *Bottom-up* models deal with single buildings and individual end-users. Energy consumption is calculated at a single building scale and then aggregated at different levels, considering an integrated framework. Among this typology of models, a further differentiation is possible, between *statistical* and *physics-based* models. The *statistical* (or *data-driven*) models use data mining and machine learning techniques to assess the energy demand of buildings (Mastrucci et al., 2014). The *physics-based* (or *engineering*) models deal with detailed modelling and simulation techniques derived by building energy modelling (Stephan et al., 2013; Fonseca et al., 2016)).

3. Life Cycle Assessment

The description and the energy modelling of the buildings give the energy employed in the use-phase and the characteristics of each building (e.g., building fabric) as an outcome. The second step, associates and combines these results to perform an LCA study. In this section, the methodologies available in the literature to perform the four steps of LCA for large building stocks are analysed.

3.1. Goal definition and scopes

The main goal of LCA applied to large-scale building stock is the assessment of sustainability considering a life-cycle approach to support urban planning and policy-making by decision-support and eco-design. Usually, decision-support studies are conducted at an early stage of design (Riera Pérez and Rey, 2013), while, eco-design studies deal mainly with evaluation scenarios in terms of buildings and spaces features (Stephan et al., 2013). Two main streams of investigations are identified: evaluation of the impacts at the current state and of future scenarios. The choice of the Functional Unit (FU) is quite heterogenous on LCA studies regarding large building stocks, depending on the objectives to reach. A vast typology of FUs are used (e.g., absolute, spatial or per capita), however, in some studies, the FU is not explicitly defined. Many authors use as FU the heated or living floor area (Trigaux et al., 2014; Sartori and Calmon, 2019), to make direct comparisons among different building stocks. Per inhabitant or per person FUs are also widely used (Heeren et al., 2013) to compare different life cycle stages and sectors. Absolute FUs are also adopted (Saner et al., 2013) however, the derived comparisons could be misleading considering that researchers studied different large areas that are largely heterogeneous (their density ranges from 370 inhabitants/m^2 (Nichols and Kockelman, 2014) to 34,400 inhabitants/m^2 (Li and Wang, 2009)). Sometimes a combination of different FUs is used (Norman et al., 2006). The service life of buildings is fundamental to assess the building life cycle, and also for this, heterogeneous approaches are used. Some authors assign fixed service life to buildings. For new buildings, a typical value is from 50 to 100 years (Norman et al., 2006; Stephan et al., 2013), while for existing buildings is usually set a residual life varying from 35 to 50 years.
The LCA model of a large-scale urban area is complex and thus the definition of the scope. Two main aspects have to be taken into account in this step: the boundaries and life cycle phases to consider. In fact, a large heterogeneity is reported in the studies, depending on the specific goal. Four main fields of the built environment are indicated: buildings, open spaces, energy networks and mobility (Lotteau et al., 2015). Just very few studies consider all the fours aspects (Stephan et al., 2013; Nichols and Kockelman, 2014; Norman et al., 2006) while others consider only buildings (Davila and Reinhart, 2013) and others neglect mobility. The possible life cycle phases to consider are production (extraction and

manufacturing), construction (transport and actual construction), use (actual use and maintenance) and end-of-life (deconstruction, transport and disposal or recycling). The production and use phases are considered in almost all the studies because they are strictly connected with the building stock modelling step (exceptions are addressed in Table 1). Also, few studies consider the end-of-life phase (Anderson et al., 2015). This differentiation is mainly due to the final aim of the study, some authors are focused on the end-of-life of building stocks (Mastrucci et al., 2017), while others are more focused on the comparison of different energy conservation measures in the building stock (Norman et al., 2006).

3.2. Inventory

The inventory step regards the collection of inputs and outputs of materials and energy within the boundary of the considered system. A distinction must be done between foreground and background data (EC JRC, 2010), respectively what is and what is not in the control of who is performing the LCA (Mastrucci et al., 2017). The foreground data consists of materials and construction data, building operation data, end of life data and mobility data. The materials and construction are usually derived from local GIS datasets, building registers, statistical data, real estate market databases, national building libraries, surveys, guidelines and case studies. These data can be also directly taken by the process of the description of the building stock. The operation data are then derived from the energy modelling step, if the modelling does not include all the needed output (e.g., water usage, waste production) some integrations with average statistical data can be performed (Nichols and Kockelman, 2015). The end-of-life data is usually derived from the used materials in the construction phase but more often average data from the available databases are employed. The mobility data are derived from regional or national averages (Norman et al., 2006) or from the normative method (Riera Pérez and Rey, 2013). The background data (e.g., extraction of raw materials for building components and transport, production of electricity, etc) are usually derived from process-based LCA databases (Ecoinvent, Gabi), and the average energy mixes are employed.

3.3. Impact assessment

In LCA studies on large building stock, the mid-point impact assessment method is the most used. In particular, Global Warming Potential and Primary Energy are chosen because they are the two key drivers for policymaking in the built environment. Very few studies considered also other categories, such as the Particular Matter Formation (Saner et al., 2014), abiotic depletion potential (Li and Wang, 2009) or land use (Trigaux et al., 2017). The use of a few indicators may lead to the definition of policies that determine the burden-shifting among different impact categories. The optional elements of normalization and weighting are not usually used in the type of studies under review (exceptions are (Wang and Li, 2015; Trigaux et al., 2014; Anderson et al., 2015; Lavagna et al., 2018)).

3.4. Interpretation

During the interpretation phase, the results are checked and summarized to provide recommendations regarding the goal and scope of the study. The common steps are contribution analysis, uncertainty and sensitivity analysis and spatial visualization of the results. Most of the authors performed the contribution analysis to assess which are the most impactful phases of the system. Generally, almost all agree that production and use phases are the most impactful compared to other phases. Just a few authors (as reported in Table 1) performed a proper uncertainty or sensitivity analysis due to the complexity of run simulations on large-scale and applied LCA to such heterogeneous systems. Finally, the visualization of results is usually GIS-based, providing maps and 3D visuals that are effective and explicit. This is fundamental to achieve good communication with stakeholders and policymakers.

4. Limitations and conclusions

This paper reviews the scientific literature that deals with the LCA studies of large building stocks, trying to retrace the methodologies employed in the literature. To achieve trustworthy results, a modelling of the building stock is followed by an LCA study. The use of a not reliable building stock modelling method could result in unrealistic conclusions. Especially the employed description method can bring to large differences in the final accuracy of the results. Thus, this first phase is fundamental to achieve solid results because the inventory and energy modelling depend strongly on it. Besides the limitations of these methods, it is fundamental to study new approaches to implement LCA studies on large building stocks modelling. Considering only the use phase is relatively simple, however, it is a very limited approach that does not give an answer to policymakers and designers that ask to evaluate the implementation of different energy conservation measures. In addition to the consideration of more Life-Cycle phases, it is important to reach a more holistic approach considering more Boundaries of cities (such as open spaces, energy networks and mobility). Lastly, to boost comparisons between studies, a more structured method should be proposed together with a common nomenclature to follow. Nowadays, the lack of a common approach is the main obstacle to the development of such methodologies.

5. References

Anderson, John E., Gebhard Wulfhorst, and Werner Lang. 2015. “Expanding the Use of Life-Cycle Assessment to Capture Induced Impacts in the Built Environment.” *Building and Environment* 94: 403–16. https://doi.org/10.1016/j.buildenv.2015.08.008.

Davila, Carlos Cerezo, and Christoph Reinhart. 2013. “Urban Energy Lifecycle: An Analytical Framework To Evaluate the Embodied Energy Use of Urban Developments.” *13th Conference of International Building Performance Simulation Association (BS2013)*, 1280–87. http://www.ibpsa.org/proceedings/bs2013/p_1351.pdf.

Fonseca, Jimeno A., Thuy An Nguyen, Arno Schlueter, and François Marechal. 2016. “City Energy Analyst (CEA): Integrated Framework for Analysis and Optimization of Building Energy Systems in Neighborhoods and City Districts.” *Energy and Buildings* 113: 202–26.

https://doi.org/10.1016/j.enbuild.2015.11.055.

Heeren, Niko, Martin Jakob, Gregor Martius, Nadja Gross, and Holger Wallbaum. 2013. “A Component Based Bottom-up Building Stock Model for Comprehensive Environmental Impact Assessment and Target Control.” *Renewable and Sustainable Energy Reviews* 20: 45–56. https://doi.org/10.1016/j.rser.2012.11.064.

Herfray, Gregory, and Bruno Peuportier. 2010. “Life Cycle Assessment Applied to Urban Settlements.” *SB10 Mad*, 1–11. http://www.sb10mad.com/%5Cnhttp://circe.cps.unizar.es/enslic/texto/scientific_5.pdf.

ISO. 2006. “ISO 14040: 2006 - Environmental Management: Life Cycle Assessment - Principles and Framework.”

Lavagna, Monica, Catia Baldassarri, Andrea Campioli, Serena Giorgi, Anna Dalla Valle, Valentina Castellani, and Serenella Sala. 2018. “Benchmarks for Environmental Impact of Housing in Europe: Definition of Archetypes and LCA of the Residential Building Stock.” *Building and Environment* 145 (September): 260–75. https://doi.org/10.1016/j.buildenv.2018.09.008.

Li, Dong, and Rusong Wang. 2009. “Hybrid Emergy-LCA (HEML) Based Metabolic Evaluation of Urban Residential Areas: The Case of Beijing, China.” *Ecological Complexity* 6 (4): 484–93. https://doi.org/10.1016/j.ecocom.2009.09.002.

Lotteau, Marc, Philippe Loubet, Maxime Pousse, Emmanuel Dufrasnes, and Guido Sonnemann. 2015. “Critical Review of Life Cycle Assessment (LCA) for the Built Environment at the Neighborhood Scale.” *Building and Environment* 93 (P2): 165–78. https://doi.org/10.1016/j.buildenv.2015.06.029.

Lotteau, Marc, Grace Yepez-Salmon, and Nicolas Salmon. 2015. “Environmental Assessment of Sustainable Neighborhood Projects through NEST, a Decision Support Tool for Early Stage Urban Planning.” *Procedia Engineering* 115 (2009): 69–76. https://doi.org/10.1016/j.proeng.2015.07.356.

Mastrucci, Alessio, Olivier Baume, Francesca Stazi, and Ulrich Leopold. 2014. “Estimating Energy Savings for the Residential Building Stock of an Entire City: A GIS-Based Statistical Downscaling Approach Applied to Rotterdam.” *Energy and Buildings* 75: 358–67. https://doi.org/10.1016/j.enbuild.2014.02.032.

Mastrucci, Alessio, Antonino Marvuglia, Ulrich Leopold, and Enrico Benetto. 2017. “Life Cycle Assessment of Building Stocks from Urban to Transnational Scales: A Review.” *Renewable and Sustainable Energy Reviews* 74 (December 2016): 316–32. https://doi.org/10.1016/j.rser.2017.02.060.

Mastrucci, Alessio, Antonino Marvuglia, Emil Popovici, Ulrich Leopold, and Enrico Benetto. 2017. “Geospatial Characterization of Building Material Stocks for the Life Cycle Assessment of End-of-Life Scenarios at the Urban Scale.” *Resources, Conservation and Recycling* 123: 54–66. https://doi.org/10.1016/j.resconrec.2016.07.003.

Nichols, Brice G., and Kara Kockelman. 2015. “Urban Form and Life-Cycle Energy Consumption: Case Studies at the City Scale.” *Journal of Transport and Land Use*, no. May. https://doi.org/10.5198/jtlu.2015.598.

Nichols, Brice G., and Kara M. Kockelman. 2014. “Life-Cycle Energy Implications of Different Residential Settings: Recognizing Buildings, Travel, and Public Infrastructure.” *Energy Policy* 68: 232–42. https://doi.org/10.1016/j.enpol.2013.12.062.

Norman, Jonathan, Heather L. MacLean, and Christopher A. Kennedy. 2006. “Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions.” *Journal of Urban Planning and Development* 132 (1): 10–21. https://doi.org/10.1061/(asce)0733-9488(2006)132:1(10).

Riera Pérez, Maria Gracia, and Emmanuel Rey. 2013. “A Multi-Criteria Approach to Compare

Urban Renewal Scenarios for an Existing Neighborhood. Case Study in Lausanne (Switzerland).” *Building and Environment* 65: 58–70. https://doi.org/10.1016/j.buildenv.2013.03.017.

Saner, Dominik, Niko Heeren, Boris Jäggi, Rashid A Waraich, and Stefanie Hellweg. 2013. “Housing and Mobility Demands of Individual Households and Their Life Cycle Assessment.” *Environmental Science & Technology* 47 (11): 5988–97. https://doi.org/10.1021/es304084p.

Saner, Dominik, Carl Vadenbo, Bernhard Steubing, and Stefanie Hellweg. 2014. “Regionalized LCA-Based Optimization of Building Energy Supply: Method and Case Study for a Swiss Municipality.” *Environmental Science & Technology* 48 (13): 7651–59. https://doi.org/10.1021/es500151q.

Sartori, Thais, and João Luiz Calmon. 2019. “Analysis of the Impacts of Retrofit Actions on the Life Cycle Energy Consumption of Typical Neighbourhood Dwellings.” *Journal of Building Engineering* 21 (May 2018): 158–72. https://doi.org/10.1016/j.jobe.2018.10.009.

Stephan, André, Robert H. Crawford, and Kristel de Myttenaere. 2013. “Multi-Scale Life Cycle Energy Analysis of a Low-Density Suburban Neighbourhood in Melbourne, Australia.” *Building and Environment* 68: 35–49. https://doi.org/10.1016/j.buildenv.2013.06.003.

Swan, Lukas G., and V. Ismet Ugursal. 2009. “Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques.” *Renewable and Sustainable Energy Reviews* 13 (8): 1819–35. https://doi.org/10.1016/j.rser.2008.09.033.

Trigaux, D., K. Allacker, and F. De Troyer. 2014. “Model for the Environmental Impact Assessment of Neighbourhoods.” *WIT Transactions on Ecology and the Environment* 181: 103–14. https://doi.org/10.2495/EID140091.

———. 2017. “Life Cycle Assessment of Land Use in Neighborhoods.” *Procedia Environmental Sciences* 38: 595–602. https://doi.org/10.1016/j.proenv.2017.03.133.

United Nations. 2015. “About the Sustainable Development Goals - United Nations Sustainable Development.” 2015. https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

———. 2018. “World Urbanization Prospects - Population Division - United Nations.” 2018. https://population.un.org/wup/DataQuery/.

Vuuren, Detlef P. van, Monique Hoogwijk, Terry Barker, Keywan Riahi, Stefan Boeters, Jean Chateau, Serban Scrieciu, et al. 2009. “Comparison of Top-down and Bottom-up Estimates of Sectoral and Regional Greenhouse Gas Emission Reduction Potentials.” *Energy Policy* 37 (12): 5125–39. https://doi.org/10.1016/j.enpol.2009.07.024.

Wang, Shang, and Yuguo Li. 2015. “Suitability of Acrylic and Copper Globe Thermometers for Diurnal Outdoor Settings.” *Building and Environment* 89: 279–94. https://doi.org/10.1016/j.buildenv.2015.03.002.

Zhang, Qingyuan. 2004. “Residential Energy Consumption in China and Its Comparison with Japan, Canada, and USA.” *Energy and Buildings* 36 (12): 1217–25. https://doi.org/10.1016/j.enbuild.2003.08.002.