Balancing data requirement and modelling quality in neighbourhood life cycle assessments

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Abstract. Introduction: When modelling complex systems such as cities, a quality-complexity compromise is to subdivide them into smaller cells. Life Cycle Assessment can help to comprehensively handle urban intricacies but is a data-intensive technique. Balancing data requirement and collection feasibility while acknowledging uncertainty become key. Methods: This research explored top-down and bottom-up approaches to generate information input for environmental modelling at neighbourhood scale and to identify strategies to improve modelling while balancing data collection needs. SimaPro v.9 supported the assessments. Results: Influence of elements like interior finishes and wall partitions is not captured by the top-down approach, but should not be neglected, for their impacts are substantial. Modelling can be improved by application of cut-off rules to limit data requirements and cluster sampling techniques to derive a minimum range of archetypes to adequately describe the studied area. Finally, an evolutive hybrid approach is suggested to gradually improve both background archetypes and foreground bottom-up objects.

Keywords: life cycle assessment, neighbourhood scale, data quality, data aggregation.

1. Introduction

Social and economic development depends on the sustainable management of the planet’s natural resources [1]. Production and operation of the built environment involves 36% of global final energy use and 39% of energy-related carbon dioxide (CO₂) emissions [2]. Therefore, assessing the existing built environment impact on nature; detecting hotspots and developing strategies to support decision-making on retrofitting and/or future sustainable urban planning take a critical stride not only towards protecting the planet from degradation; but also for sustainable development goals (SDG) related to building resilient infrastructure (SDG 9); achieving climate change mitigation goals (SDG 13); and enabling resilient and sustainable cities (SDG 11).

Cities are complex, long-lasting systems that amalgamate human and ecological processes happening simultaneously at the same time and space. Assessments at this scale become difficult to accomplish due to urban ecosystems’ hybrid, multi-equilibria and hierarchical properties, wherein the interactions between multiple agents at the local level and among them and their environment determine patterns at higher levels [3]. Hence, when attempting to handle urban intricacies, a complexity compromise is to subdivide the urban area into smaller cells such as neighbourhoods, which represent the typical scale for urban development projects.

From a variety of tools and methods suitable for environmental assessment of urban areas, Life Cycle Assessment (LCA) offers a powerful conceptual methodology and stands out due to its ability to avoid burden shifting across life cycle stages, environmental impacts and territories [4] and its ability to provide urban decision-makers with comprehensible information on environmental sustainability [5]. Nevertheless,
due to its comprehensiveness, detailed scope and multi-criteria assessment potential, LCA is a data intensive approach. Given the neighbourhood scale idiosyncrasies, data challenges are intensified. As the reliability of LCA outcomes depends on the quality of the original background data, ‘data quality’ management should be an integrated part of the process [6]. Thus, finding balance between required and feasible information collection, and determining the best way to handle data quality and uncertainty should be a priority when pursuing reliable results.

Process LCA (bottom-up) application to highly aggregated system like whole-buildings and neighborhood is challenged by the large number of materials, lack of production data and numerous inferences made over time. Practice calls for modelling simplification, mostly through inventory reduction (cutoffs) [7]. Economic input-output LCA (EIO-LCA) can potentially help to fill in inventory data gaps in situations of limited data availability. EIO-LCA uses publicly available, reproducible results to link monetary values with physical units and provide (environmental) information on every commodity in the economy. In general, these models lack data for complete environmental effects, and their usefulness is limited by the very factors that make them efficient and robust, namely the power of aggregating-disaggregating data based on changes in demand for industry sectors. As a given industry sector represents a collection of several industry types, aggregation level of the model chosen can lead to uncertainty in the modelling of a specific industry. Also, most national models, when available, are too aggregated. The number of sectors represented in the economy should be enough to minimize disaggregation uncertainty. Most models – including those available for Brazil - have only 100 sectors or less representing all industries. If EIO-LCA are most useful at national, highly aggregated, level. At neighborhood scale, its usefulness is possibly more limited as it depends on availability of adequate models and of environmental information to inform them at this granularity level.

This paper investigates how data collection and modelling methods influence the data requirement-modelling quality balance in neighbourhood LCA. It represents the first of a three-phased research project aimed at developing a methodological framework. In this first phase, two LCAs were performed in a single urban block of a chosen neighbourhood case study, using top-down (TD) and bottom-up (BU) data aggregation approaches. The second phase of the research will apply a hybrid approach on a five-block cluster within the neighbourhood and calibrate the method against the benchmark established in this first phase. Finally, the final hybrid approach will be validated for the entire neighbourhood.

2. Methods

To achieve the above-mentioned goal, two life cycle assessments were carried out for a selected case study block in the University of Campinas’ Campus. First, general ground rules were established for each approach to avoid methodological bias. For the TD approach, mainly national, regional or local data based on archetype could be used. For the BU approach, the existing buildings’ design and site surveys assisted in modelling the pilot area using a BIM tool. Second, the life cycle inventory (LCI) for each approach was developed following the preset ground rules. Third, both LCAs were performed following identical steps and methodological choices in terms of goal, scope, reference study period, building performance, functional unit, system limitations, inventoried data, impact assessment methods and indicators (see table 1). Finally, results from both approaches were compared.

2.1. Case description

Located in the municipality of Campinas, the campus total built area is equivalent to 581,003m²/601,012m² and comprise mixed uses, such as: administration, education (classrooms), research (laboratories, workshops), health facilities (hospitals, clinics), libraries, restaurants, cultural facilities, sport facilities, general services, day care centre, school, bank agencies, squares, public spaces and more [9].

Based on data availability and prior knowledge, Block 43 was assessed as the smallest feasible urban cell (Figure 1).
Figure 1 - Contribution analysis per life cycle phase (TD approach)

It comprises 15 buildings and surrounding environment in 52,523.58m², encompassing structure, exterior and interior walls, stairs, finishes, windows and doors, installations and building services, as well as the infrastructure enclosure, energy network (light poles and PV panels) and street network. All buildings followed the same construction technology regarding foundation, structure and exterior walls. While some materials differ from components, such as floor and roof tiles, others were found in all buildings, e.g. reinforced concrete structure, aluminium and wood windows/doors and hydro sanitary ceramics.

2.2. Methodological Choices

In terms of system boundaries, the scope of the study included: raw material extraction, transport to manufacturing site and manufacturing of the product itself in the product stage (Modules A1-A3); transport of the product to the construction site and installation activities in the construction process (Modules A4-A5); replacement, operational energy use and operational water use in the use stage (Modules B4 and B6-B7); and deconstruction and transport to waste/recycling processing sites in the end of life stage (Modules C1-C2) [10]. The functional unit adopted was square meter in a reference study period was 50 years.

At this point of study, we chose to exclude modules B1-B3, B5, B7 and C3-C4 (regarding use, maintenance, repair, refurbishment, waste processing and disposal). The lack of consistent available data imposed a number of limitations: (i) excluding underground infrastructure, energy substations and cables, green areas and green roofs in the assessment; (ii) assuming 100% of material substitution in the replacement module; (iii) grouping all types of concrete into three categories, according with the fck (fck 25, fck 35, and prefabricated concrete fck 35); (iv) not accounting for grouting and reinforcing steel of concrete block structures; (v) grouping all types of steel simply into reinforcing or galvanized steel; (vi) standardizing all cement as Portland cement CPII; (vii) considering only external paint finishing; and (viii) only differentiating street network modelling by the quantification method (autocad/BIM vs. google earth), as both approaches used TD data.

The background system for both approaches was mainly composed by coefficient values estimated using Ecoinvent 3 4 and 3.5 as background data source, Cumulative Energy Demand (CED) v1.11 and CML-IA baseline v3.05 impact assessment methods and its adaptation to the Brazilian energy matrix using SimaPro 9. In the absence of background data, three environmental product declarations were used (for vinyl tile, asphalt mixture and stainless steel). Finally, thirteen impact categories were considered: Non-Renewable Primary Energy; Renewable Primary Energy; Abiotic Depletion; Abiotic Depletion (Fossil Fuels) ADP fossil; Global Warming Potential; Ozone Layer Depletion; Human Toxicity; Freshwater Aquatic Ecotoxicity; Marine Aquatic Ecotoxicity; Terrestrial Ecotoxicity; Photochemical Oxidation; Acidification Potential (AP); Eutrophication Potential (EP). Table 1 summarizes the main methodological choices.
### Table 1 – Summary of main methodological choices

| Goal | Comparison of two LCAs of an urban block using two different modelling approaches (Bottom-up and Top-down) |
|------|-------------------------------------------------------------------------------------------------------|
| Scope | Cradle to grave (A1-A5; B4, B6; C1-C2) |
| Reference study period | 50 years |
| Building Performance | ABNT NBR 15575 [26] |
| Functional unit | m² |
| System limitations | Removal of B1-B3, B5, B7 and C3-C4 stages; EEG adaptations; Use of three EPDs |
| Inventory data | Ecoinvent 3.4 and 3.5; EPD |
| Impact assessment methods | Cumulative Energy Demand (CED) v1.11 and CML-Ia baseline v3.05 |
| Indicators | CED; ADP; ADP fossil; GWP; ODP; HTTP; FAETP; Marine Aquatic Ecotoxicity; Terrestrial Ecotoxicity; POCP; AP; EP |

#### 2.2.1. Top-down (TD) approach

The foreground system for the TD approach comprehended: (i) choosing an archetype that best represented all campus buildings; (ii) acquiring the design project documentation for the building with the campus administration; (iii) extracting basic information about the building in regards to its ground floor area, number of floors, floor height (from slab to slab), roof height, total building height, technical area and GFA; (iv) quantifying the operational energy and water yearly demand, in the same way as the BU approach; (v) developing a LCI equally detailed, using the same methodological choices as the BU approach; (vi) collecting data on the ground floor area of each building in the urban block analysed using google earth; (vii) and extrapolating the archetype material, energy and water consumption results to the buildings in the urban block, using their ground floor area as reference value.

#### 2.2.2. Bottom-up (BU) approach

In the BU approach, the foreground system of the LCI analysis comprised more refined data. Design documentation of all buildings and street network was provided by the campus administration. The bill of materials and gross floor area (GFA) were extracted from BIM models informed by the Civil Construction Costs and Indexes Research National System (SINAPI). Material wastage estimates were supported by Budget Compositions and Prices Table [11]. The energy consumed in modules A1-A5 was estimated based on literature [12]. The 2019 energy and water bills were divided by the total GFA within the campus, then multiplied by each building GFA to obtain disaggregated annual operational energy and water demands.

Distances between the construction site and the nearest materials manufacturers were estimated by Google maps. Construction elements’ service life was established by Brazilian building performance standard ABNT NBR 15575:2013 [13]. The waste and recyclability shares of all replacement and EOL mass were extracted from the Sectorial Survey of the Brazilian Association for the Recycling of Construction Waste and Demolition [14].

Data required to quantify environmental impacts increase in the neighbourhood scale. Building Information Modelling (BIM) was then used for enabling a 3D digital representation of a building’s characteristics through its lifespan, and providing opportunities to share information with multiple stakeholders [8]. The BU approach benefited from bills of materials automatically extracted from BIM models. Command of Revit 2019 and partially pre-developed 3D models in that software naturally drove our option towards it. Still, complementary information gathering was necessary due to buildings’ age differences. The missing data was obtained through architectural and structural 2D projects, photographic survey and online tools such as Google Maps and Street View.

The quantity extraction process adopted a building element survey, followed by complementary information from SINAPI - with a detailing limitation based on relevance and overall percentage within a building element (e.g. sanitary metals and clamping elements).
3. Results and discussion

A life cycle outlook highlights contribution discrepancies. The life cycle impact profile obtained through the TD approach is dominated by the operational energy’s contribution (Figure 2). Contrastingly, contribution analysis at building elements level highlights replacement’s influence (Figure 4), particularly regarding wall partitions, interior finishings and - to a lesser extent - façades, on BU results (Figure 5). Indeed, the national standard ABNT NBR 15575 induces more frequent replacements than its international counterparts. Absolute operational electricity obtained with BU and TD approaches differ by only 3%. Hence, the increased absolute impact values obtained with the BU approach mostly reflect the intensive wall partitions replacement, which were not considered in the TD approach.

In this study, no cutoff rules were applied to the BU life cycle inventory, but the European standard EN 15804:2012 (CEN, 2012) cut-off criteria admit excluding items which represent less than 1% of the total mass input AND energy usage of unit processes, as long as the total neglected input flows per module do not exceed 5% of the total mass or energy. However, elements involving material and energy flows known to have the potential to cause significant impacts should not be disregarded, even if compliant with the limit established. Previous and ongoing research by the authors’ group suggest that, by applying the EN 15804:2012 mass-and-energy cutoff rule, about 45% and 62% for the cases studied by [7] - of material production processes would be excluded from the inventory, while still covering over 80% of the baseline product stage impacts. Applying such cutoff criteria saves a significant workload, which can be redirected to improve archetype definition and other assessment refinements.

3.1. Top-down (TD) approach

In general, the TD approach underestimated overall impacts. Water and energy consumption in construction operation and demolition were also overestimated by the use of fixed factors per m² of GFA, extracted from literature and can be refined from now on based on the BU results achieved. Wall partitions, stairs, interior finishings and windows/doors elements show the largest discrepancies, which range between about 82% and 100%. This suggests that the changes in the original design over time should not be neglected and the archetype – or collection of archetypes - could be more detailed for improved representation.

The main impact contributors in the TD approach were concrete, reinforcing steel, asphalt mixture (Figure 3). Yet, galvanized steel and aluminium frame stood out and clearly surpassed concrete and asphalt mixture’s contribution when the inventory was detailed by the BU approach. This explains why the highest discrepancies were registered precisely for the building elements in which these materials were present.

Figure 2 - Contribution analysis per life cycle phase (TD approach)
Figure 3 - Contribution analysis of Building elements’ impacts (TD approach)

Influence of interior finishings, wall partitions – and to a lesser extent - stairs and windows/doors is not captured by the TD approach, but should not be neglected, for their impacts are substantial. Interior finishings alone respond for about 94% of abiotic depletion potential (ADP); 82% of terrestrial ecotoxicity and 60% of eutrophication potential. On their turn, wall partitions alone cause about 90% marine aquatic ecotoxicity. Interior finishings and wall partitions, combined, induce about 47% of abiotic depletion (fossil fuels); 43% of global warming and ozone layer depletion; 61% of acidification; 64% of freshwater aquatic ecotoxicity; and 75% of human toxicity potentials. Interior finishings and façades respond roughly equally for ~62% of photochemical oxidation potential. Together, interior finishings, wall partitions, stairs, windows and doors cause relevant EEren (36%), GWP (43%) and EEnren (50%) impacts.

3.2. Bottom-up (BU) approach

Adherence of each studied building to the archetype’s material and operational description suggests that a small range of archetypes is necessary for satisfactorily describing built clusters within a given area (e.g. a deviation of less than 10% from the archetype’s overall impacts, for at least 80% of the buildings considered).
Figure 4 – Contribution analysis per life cycle phase (BU approach)

Figure 5 – Contribution analysis of Building elements’ impacts (BU approach)

4. Final remarks and next steps

This research explored top-down and bottom-up approaches to generate information input for environmental modelling at neighbourhood scale and identify strategies to improve modelling while balancing data collection needs. Indeed, influence of interior finishings, wall partitions – and to a lesser extent - stairs and windows/doors is not captured by the TD approach, but should not be neglected, for their impacts are substantial.

An evolutive hybrid approach will be pursued to gradually improve both background archetypes and foreground BU objects, comprising, among others:
• Context analysis of the neighbourhood (cultural and construction aspects, data gathering on the location);
• Walkthrough the neighbourhood to identify general aspects and construction characteristics to be considered in the analysis;
• Archetype definition complementation through visual/image analysis;
• Bottom-up approach LCA of the chosen archetypes with the best data available and refinement of basic materials (by construction element).

Establishment of a data quality scale into e.g. levels 1, 2, 3 for national/regional/local estimates; level 4 (local estimate plus local typology), 5 (local estimate plus varied local typologies); 6 (simulated design) and 7 (in situ measurement/survey), to identify how each data type should be handled in terms of uncertainty and sensitivity analysis.

Cut-off rules can limit data requirements and improve modelling. Cluster sampling techniques will also applied to derive a minimum range of archetypes to adequately describe the studied area. When most of the variation in the population occurs within the clusters (i.e. a given archetype describing a relatively homogenous group of buildings) - and not between them - the expected random error is smaller.

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