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Kanafani, Kai; Garnow, Agnes; Zimmermann, Regitze Kjær; Sørensen, Christian Grau; Brisson Stapel, Emilie; Birgisdottir, Harpa

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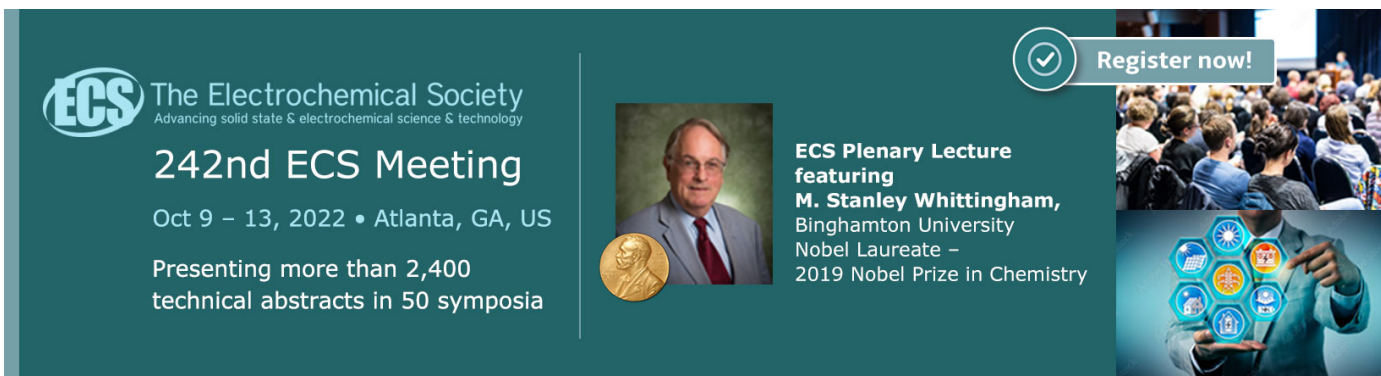
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# Automated Life cycle inventories for existing buildings – a parametric reference model approach

**K Kanafani<sup>1</sup>, A Garnow<sup>1</sup>, R Zimmermann<sup>1</sup>, C Sørensen<sup>1</sup>, E Stapel<sup>1</sup> and H Birgisdottir<sup>1</sup>**

<sup>1</sup> BUILD, Aalborg University, A.C. Meyers Vaenge 15, 2450 Copenhagen, Denmark

**kak@build.aau.dk**

**Abstract.** Buildings account for 40% of global Greenhouse gas (GHG) emissions. In heating-dominated climates, most building-related emissions originate from building stock operational energy, especially from buildings constructed before energy requirements were introduced. Renovation can mitigate operational emissions, however, materials should be included to increase the mitigation potential. Life-cycle assessment (LCA) includes emissions from materials and energy but are time-consuming in renovations because BIM-aided approaches for automating inventories are inaccessible for existing building fabric. This paper proposes a parametric inventory-generator for existing buildings, which defines material quantities through few key variables, which are accessible in early design stages, and which relate to a reference model for a specific building type. The generated model includes LCA inventory data such as service life, replacements, and End of Life from a generic impacts database. The model is adjustable and can be supplied with predefined renovation interventions and new components. The proposed simplification has potential to facilitate modelling of LCA inventories for every existing building, and makes LCA feasible for more than deep renovations, offering a base for the proposed renovation pass by the EU commission. Future research will add building types and explore implementing default inventories based on cadastre data as public resource.

**Keywords.** Renovation, LCA, whole-life carbon assessment, early design, parametric model generator

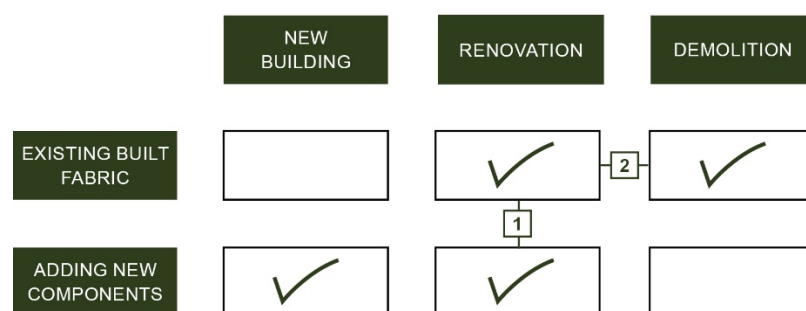
## 1. Introduction

With the Paris-agreement [1] many countries have agreed on committing to limit global warming to 2.0 degrees with an aspiration to 1.5 degrees. The European Union member states have agreed to reduce GHG emissions by 70% in 2050 compared with 1990 levels. Carbon mitigation is especially relevant in the building sector, as it represents almost 40% of greenhouse gas (GHG) emissions [2]. Since 85-95 % of the building stock (EU) will still exist in 2050 [3], mitigating GHG emissions in the building stock is inevitable and strong policy instruments for more and deeper renovations are discussed in the EU Renovation Wave initiatives, including mandatory energy retrofits [3, 4].

The dominant method for determining whole-life building impacts is life cycle assessment (LCA) based on the EN 15978 [5] and related CEN TC350-standards, also being the key element in the European Commission's LCA scheme Level(s). However, it is commonly agreed that rules for LCA require a translation from the more theoretical definitions given in EN 15978, to practical



implementation in actual policy schemes [6–8]. Taking into account the current premature state of LCA-implementation in the building industry, effective carbon regulation must include both a simplification of the EN 15978 scope, which is too comprehensive for application in specific building projects, and tools for efficient LCA workflows. Regarding method simplification, any of the currently emerging national carbon regulations for buildings apply some degree of method simplification [9–13], as whole-life carbon emissions are becoming a regular building performance indicator. Key to any building LCA tool is establishing and managing a building material inventory (building model), which is the most time-consuming procedure and therefore possesses a potential productivity improvement. Material inventories are required in all building LCA applications (Figure 1) and may include both existing and new components. Common for all LCA applications is that most building carbon emissions are determined in early project stages [14–16].



**Figure 1.** Need for material inventories in various LCA applications. Inventories of the existing built fabric can be reused in two ways, (1) for quantifying added components in renovations and (2) for inventorying a demolition case i.e. when comparing scenarios for renovation with demolition and new building

Known approaches for increasing productivity in generating material inventories include

1. Developing GHG reference emission values for on building or or building element level
2. Linking LCA with geometric models (3d CAD, BIM)
3. Developing generic product and component libraries
4. Deriving generic material quantities

Applying reference emission data are the quickest and simplest way of estimating carbon emissions of a building typology or parts of the building model, however they lack the possibility of controlling results and adjusting the LCA-model to project specific parameters. Since they do not provide an LCA-model, reference data cannot be reused in subsequent projects stages, which ultimately postpones the time-consuming modelling work to later stages.

Recent developments of linking LCA with digital design tools have shown the potential of becoming an industry standard. Even though digitalization has made these solutions more accessible, these links are not always the best choice, and some challenges remain to be solved [17, 18]. Most of all, integration of LCA in design models are restricted to projects with comprehensive BIM or 3D workflows, which is especially challenging in small projects and renovations.

Generic product and component libraries are useful in both new building and renovation LCA. More and more of these life cycle inventory databases are emerging [19–24], mostly in support of national whole-life carbon limits regulation. Generic products and component data help establishing an initial building model and allow estimating carbon emissions already in early design, where they can replace less determined or missing material quantities.

Carbon mitigation in existing buildings is achieved by cutting operational energy consumption and renewable energy supply. Necessary interventions include a certain amount of material flow in and out of the building, adding new environmental impacts to the building account. The design of optimum renovation interventions therefore needs consideration of the trade-off between operational energy savings and embodied materials impacts. This paper focusses on the embodied emissions, since operational energy methods are well-established.

However, there is a significant difference in workflow between renovation and new buildings. Most renovation LCA approaches include the existing building fabric in the assessment [25]. Quantifying the existing building fabric is necessary for inclusion in the building's future life cycle after renovation but is not a part of renovation processes. This extra workload might exceed the effort for modelling the actual intervention and cannot be justified by the magnitude of its carbon emissions, which will often be lower in deep renovations.

### *1.1. Problem and research aim*

Despite offering significant potential for reduction of environmental impacts, the practice of renovation-LCA is not as widespread as LCA for new buildings. Barriers for the uptake of renovation LCA are lacking legal requirements, lacking method harmonization and not least the time-consuming registering of the existing building fabric. This is especially crucial in initial project stages or small-scale renovations, where the existing building fabric is not modelled in detail. Since the discussed existing approaches for simplifying the LCA process cannot be applied to quantifying the existing building fabric, renovation LCA either exceed project budgets or lack quality, both of which will hinder effective climate action.

This paper proposes a parametric inventory-generator for existing buildings. It is based on generic components and quantities calculated from a reference typology, which together provides a complete building model inventory. Input parameters must be simple and available to the practitioner in any renovation project. At the same time, it must deliver complete and detailed material quantities for allowing useful estimates of the final LCA in early design stages. Instead of a static black box benchmark, a dynamic model is required, where material choice and quantities can be adjusted depending on the specific project in the often-unique conditions with past layers of changes and renovations. Once the dynamic, structured building model has been generated, it should form the base for the LCA workflow during all remaining project stages. As the blueprint for the existing building has been generated, the method supports the process of adding renovation interventions to the building elements in question.

## **2. Method**

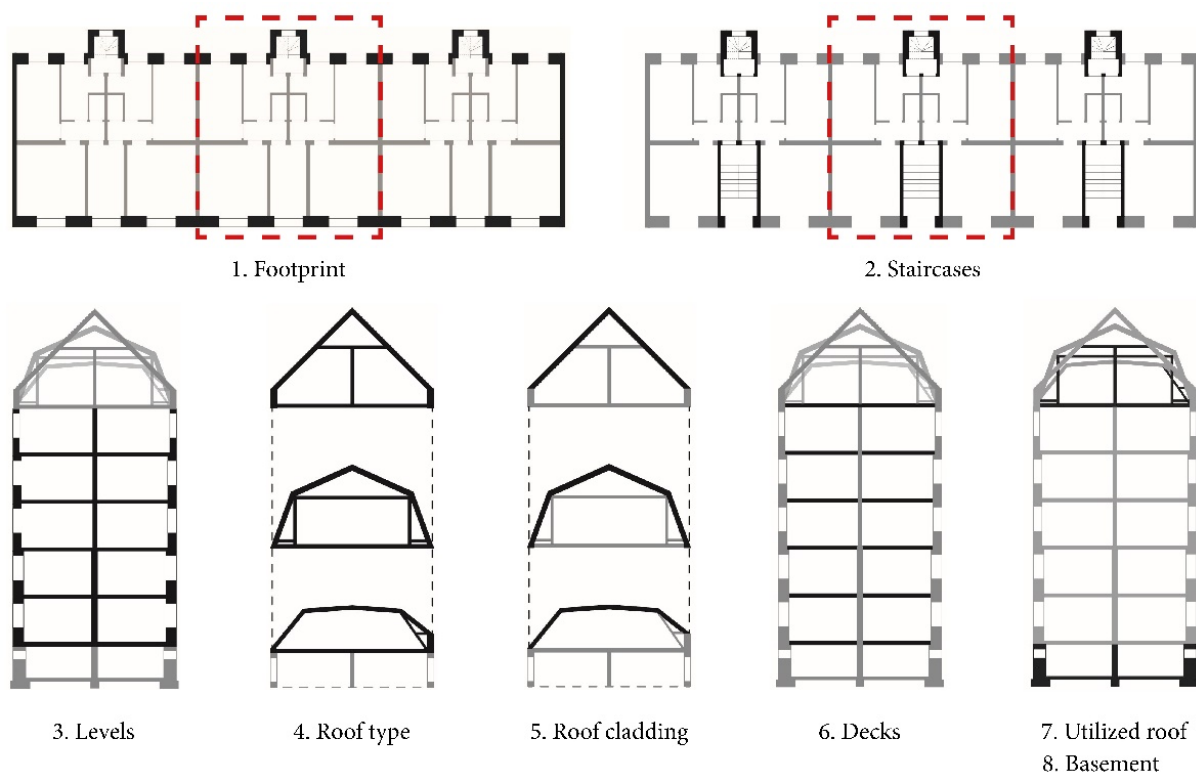
A precondition for aiding inventories for existing buildings is an analysis of building typology, detailing and material use in the building stock, which then is used to develop a parametric model. This paper is selecting one building typology as a pilot case to illustrate the method but can be extended to other typologies and building ages. The pilot is masonry apartment building typology from 1850-1920, which is typical urban housing form in most cities in Denmark.

In a first step, drawings for six buildings from four different neighborhoods were retrieved from the public building register. Floorplans, elevations, sections and details were subsequently compared to define common typology characteristics, which are relevant for a Bill of Materials used in building LCA (Figure 2). This includes two types of information, firstly the composition and area of building elements relative to a reference unit, and secondly building geometry including building depth, floor height and roof type. The typology analysis was accompanied by an existing comprehensive building typology study [26].

The found components were compiled in a generic library for existing building components (Ex-library) as a background for the LCA tool LCAbyg [27]. The retrieved building geometry information was then used for developing a generic building model. In the pilot typology, a repetitive floor plan sequence was identified and then used as a modular unit to determine component quantities (Figure 2).

Other relationships between building geometry and material quantity, such as roof or basement level or the increasing wall thickness in lower floors, were defined in a set of constants. Definitions for both the module-based and other relationships are given in Tables 2 and 3.

By combining eight user input variables (Table 1) with building geometry information and the component quantities from the Ex-library, a complete building model of any given existing building within the typology can be generated. Typical renovation intervention components (Ren-library) were developed from available professional and industry information. Components in all libraries are composed from generic products from Ökobaudat [29], which is the product level library in the LCA tool.

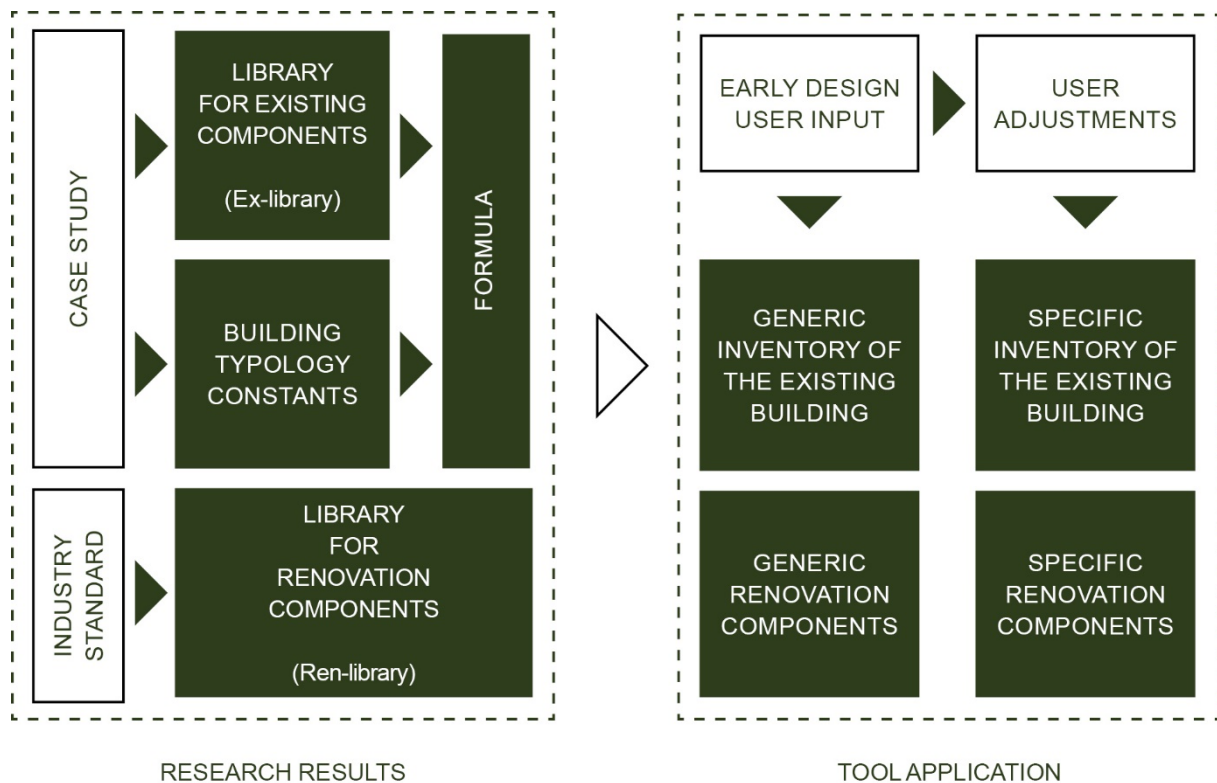


**Figure 2.** Generic case building. The modular unit is marked in red.

### 3. Results

Results of this project will be accounted for in different steps, which are explained individually in subsections. The project has introduced a new method for automatically generating inventories of the existing building fabric in renovation LCA (Figure 3). Viewed from left to right, the method for developing both component libraries and building typology constants is illustrated. The libraries with components for the existing fabric (Ex-library) allows composing a building model by providing all types of components and material choices, which are common for the building typology. To generate an existing building model, the user must define eight variables. Finally, a series of formula was developed, which combines the user input with the Ex-library and generates a fully detailed building model of the existing building fabric. It is then optional for the user to adjust element area or implement changes in the built fabric, which deviate from the original state. Since the model includes generic areas for all building elements such as walls and roofs, the generated building model can then be supplemented with specific renovation interventions from the Ren-library. Components in both libraries include quantities of building products in full detail and can be edited or replaced with user components in LCAByg [27]. An international version in English is available. Since the tool also includes an extensive

component library for new components, it supports the simple generation of comparing scenarios for preserving the existing building, renovation or demolition and replacement with a new building. Libraries, assumptions, and method for the inventory generator have been published in a background report [28].



**Figure 3.** Development of the inventory-generator and component libraries (left side) and applied LCA process with incremental refinement from a user perspective (right side).

**3.1.1. Ex-library (existing building fabric components).** Components include both items, which are specific for the chosen building typology, many are relevant for other typologies as well. Each component has a description to help evaluate its suitability. Since the components are historic, all of the production stage is omitted. Components are assembled with generic building products from Ökobaudat [29], which is the core library in the LCA tool.

**3.1.2. Ren-library (renovation intervention components).** Interventions were developed for modelling the added materials to the building in renovations. The library covers the most common interventions, which include an energy retrofit of the typology's building envelope. Building services and other, non-energy related interventions are not included. The structure of the Ren-library is similar to the Ex-library, consisting of components modelled with generic products from Ökobaudat [29]. However, renovation interventions are defined as new constructions including impacts from the production stage, and pre-defined with scalable quantities, so that project specific needs determine the size of construction. This includes insulation type and thickness.

**3.1.3. Building geometry generation.** The typology study has resulted in a number of constants and geometric relationships in the building typology, which are used to determine the component area of this building typology. The eight key variables (Table 1) include building information that is accessible in early stages of a project and do not require extensive resources to obtain.



**Table 1.** Input variables required by the user.

No.	Variable	Possible input	Formula
1	Footprint	area (m <sup>2</sup> )	input = x
2	Staircase	number	quantity staircase
3	Levels above ground	number	quantity levels
4	Roof type	1. Pitched 2. Mansard 3. Copenhagen roof	multiple choice
5	Roof cladding	1. Tiles 2. Slate 3. Zink	multiple choice
6	Deck type	1. Timber, clay-fill 2. Steel, concrete	multiple choice
7	Utilized roof floor	yes / no	
8	Basement	yes / no	

**Table 2.** Determination of building geometry through constants and user input variables.

Building geometry	Floor	Quantity	Unit	Status
Building depth	Regular floor	9,500	m	constant
Floor height	Regular floor	2,772	mm	constant
Basement height	Basement	2,046	mm	constant
Staircase area	Regular floor	16	m <sup>2</sup> / pcs.	constant * staircase number * quantity regular floors
Primary stair area	Regular floor	11	m <sup>2</sup> / pcs.	constant * staircase number * quantity regular floors
Secondary stair area	Regular floor	5	m <sup>2</sup> / pcs.	constant * staircase number * quantity regular floors
Staircase area	Ground floor	16	m <sup>2</sup> / pcs.	constant * staircase number
Secondary stair area	Roof floor	5	m <sup>2</sup> / pcs.	constant * staircase number
Secondary stair area	Basement	5	m <sup>2</sup> / pcs.	constant * staircase number

**Table 3.** Output area and calculation path from user input.

Generated area	Floor	Formula for generating areas	Share relative to footprint
Roof floor area	Roof floor	footprint - (secondary stair area * quantity staircase)	94,9%
Residential area	Regular floor	footprint - (staircase area * staircase number)	83,6%
Basement area	Basement	if yes = footprint - (secondary stair area * quantity staircase)	94,9%
Staircase area	Regular floor	primary stair * staircase number * (quantity levels -1) + secondary stair * staircase number * (quantity levels -1)	16,4%
Primary stair area	Regular floor	primary stair * quantity staircase * (quantity levels -1)	11,3%



Secondary stair area	Regular floor	secondary stair * quantity staircase * (quantity levels -1)	5,1%
Staircase area	Ground floor	staircase, ground floor * quantity staircase	16,4%
Secondary stair area	Roof floor	secondary stair * quantity staircase	5,1%
Secondary stair area	Basement	if yes = secondary stair * quantity staircase	5,1 %
Gross floor area (if 7: no)	All regular floors + Ground floor	residential area * quantity levels	
Gross floor area (if 7: yes)	All regular floors + Ground floor + Roof floor	(residential area * quantity levels) + roof floor area	

4.3.5. *Example of possible building model (output)*. The following example (Table 4) illustrates a generated building model with all components, categorized by the elements they are classified in. The generated model represents the original state of construction, which can be edited afterwards for implementing deviations from the standard assumptions or past interventions.

**Table 4.** Example of generated building model.

Building element	Component name	Formula
Roof	Pitched roof, tiled	constant * roof floor area
Deck	Roof floor, deck	constant * roof floor area
Roof	Pitched roof, secondary stair, tiled	quantity * staircase number
Exterior wall	Pitched roof, primary stair	quantity * staircase number
Exterior wall	Ground floor, primary stair	quantity * staircase number
Exterior wall	Basement, primary stair	quantity * staircase number
Exterior wall	Pitched roof, secondary stair	quantity * staircase number
Exterior wall	Ground floor, secondary stair	quantity * staircase number
Exterior wall	Basement, secondary stair	quantity * staircase number
Foundation	Foundation, secondary stair (M)	quantity * staircase number
Windows	Roof floor, primary stair, windows	quantity * staircase number
Doors	Ground floor, staircase, exterior door	quantity * staircase number
Doors	Roof floor, staircase, interior doors	quantity * staircase number
Stairs & ramps	Ground floor, primary stair	quantity * staircase number
Stairs & ramps	Roof floor, secondary stair	quantity * staircase number
Stairs & ramps	Ground floor, secondary stair	quantity * staircase number
Exterior wall	Pitched roof	constant * residential area
Exterior wall	5th floor	constant * residential area
Exterior wall	5th floor, parapet	constant * residential area
Exterior wall	4th floor	constant * residential area
Exterior wall	4th floor, parapet	constant * residential area
Exterior wall	3rd floor	constant * residential area
Exterior wall	3rd floor, parapet	constant * residential area
Exterior wall	2nd floor	constant * residential area
Exterior wall	2nd floor, parapet	constant * residential area
Exterior wall	1st floor	constant * residential area

Exterior wall	1st floor, parapet	constant * residential area
Exterior wall	Ground floor	constant * residential area
Exterior wall	Ground floor, parapet	constant * residential area
Exterior wall	Basement	constant * basement area
Foundation	Foundation (M)	constant * basement area
Foundation	Foundation (L)	constant * basement area
Windows	Basement, windows	constant * basement area
Exterior wall	Pitched roof, gable	quantity * 2
Exterior wall	5th floor, gable	quantity * 2
Exterior wall	4th floor, gable	quantity * 2
Exterior wall	3rd floor, gable	quantity * 2
Exterior wall	2nd floor, gable	quantity * 2
Exterior wall	1st floor, gable	quantity * 2
Exterior wall	Ground floor, gable	quantity * 2
Exterior wall	Basement, gable	quantity * 2
Interior wall	Ground - 5th floor, non-load-bearing wall	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (S)	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (M)	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (L)	constant * residential area * (quantity levels)
Deck	Ground -5th floor, deck, timber	constant * residential area * (quantity levels)
Windows	Ground - 5th floor, windows	constant * residential area * (quantity levels)
Doors	Ground - 5th floor, interior doors	constant * residential area * (quantity levels)
Exterior wall	1st - 5th floor, primary stair	quantity * staircase number * (quantity levels -1)
Exterior wall	1st - 5th floor, secondary stair	quantity * staircase number * (quantity levels -1)
Windows	Ground -5th floor, primary stair, windows	quantity * staircase number * (quantity levels -1)
Doors	1st - 5th floor, staircase, interior doors	quantity * staircase number * (quantity levels -1)
Stairs & ramps	1st - 5th floor, primary stair	quantity * staircase number * (quantity levels -1)
Stairs & ramps	1st - 5th floor, secondary stair	quantity * staircase number * (quantity levels -1)
Interior wall	Pitched roof, firewall	constant * (residential area / 2)
Interior wall	5th floor, firewall	constant * (residential area / 2)
Interior wall	4th floor, firewall	constant * (residential area / 2)
Interior wall	3rd floor, firewall	constant * (residential area / 2)
Interior wall	2nd floor, firewall	constant * (residential area / 2)
Interior wall	1st floor, firewall	constant * (residential area / 2)
Interior wall	Ground floor, firewall	constant * (residential area / 2)
Interior wall	Basement, firewall	constant * (residential area / 2)
Terrain deck	Basement, deck	constant * footprint
Stairs & ramps	Basement, secondary stair	yes = quantity * staircase number

#### 4. Discussion

The value of providing parametric inventory generators in an LCA tool depends on a balance between ease of required input seen from a user perspective and accuracy and adaptability of the generated

inventory. Since the selected pilot case is a historic typology, which can be applied to LCA of renovations, demolitions and building stock screenings, ease of input was more important than accuracy of results. When developing inventory generator for new buildings, this balance may be different. Also, the assumed need for the presented inventory generator relies on the inclusion of existing building fabric in renovation LCA. However, the authors believe that this methodology will become a standard approach, since embodied building emissions in the existing materials are a natural part in future building regulation and building passports. Also, parametric material quantification can offer a bottom-up approach to material bank analyses on neighborhood or national scale. The method also relies on the existence of material quantity patterns in building typology. This has shown true in this pilot case of the historic apartment typology and has to be tested for other modern typologies, which might be more difficult to quantify with a rule-based approach or could require more variables. Finally, the method is not restricted to existing buildings, as LCA become standard practice in new buildings, there is potential for further expansion and higher level of detail in libraries for new components. In the near future, the principles of the generator could be used for screening or quickly generating building models in new buildings, where potential hotspots could be identified early in the design process.

## 5. Conclusion

The parametric inventory generator based on a pilot typology has the potential of making LCA more for certain applications and under certain preconditions. Automated inventories are useful when no building model or Bill of Quantity/Materials is available, which is typically the case in early project stages or in LCA with low detail requirements such as inventories of existing buildings in renovations, new building/demolition versus renovation scenario comparison or building stock material bank screenings. A parametric approach is best suited for typologies with clear repetitive patterns in geometry and layout such as many apartment and office buildings. For more irregular typologies a statistical approach based on a large number of cases might be more appropriate.

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