Building Inventory and Refurbishment Scenario Database Development for Switzerland

York Ostermeyer,[1] *Claudio Nägeli,*[1] *Niko Heeren,*[2] *and Holger Wallbaum*[1]

[1] *Sustainable Building Group at Chalmers University of Technology, Gothenburg, Sweden*
[2] *Chair of Ecological System Design at the Swiss Federal Institute of Technology, Zurich, Switzerland*

Keywords:

building component
building stock modeling
embodied environmental impact
industrial ecology
material usage
refurbishment database

Supporting information is linked to this article on the *JIE* website

Summary

Material usage and the related embodied environmental impact have grown in significance in the built environment. Therefore, cities and governments need to develop strategies to reduce both the consumption of resources during usage phase as well as the embodied impact of the current building stock. This article proposes a new component-based building inventory database as a basis to develop such strategies using building stock modeling. The developed database clusters the building stock according to building typology (single-family houses, multifamily houses, and office buildings), age, and the main construction systems of the different building components. Based on the component makeup, it lists the necessary material input and waste output for different refurbishment options for each building component. The advantages of the proposed database structure are shown based on two applications for the developed database for Switzerland. The component-based database allows optimization of refurbishment strategies not only from an energetic perspective, but also with respect to materials, both on the input (sourcing of materials) and the output (waste streams) level. The database structure makes it possible to continuously extend the data set by adding new refurbishment options or add data such as component-specific lifetimes, costs, or labor intensities of the refurbishment options. In combination with an aligned economic model, this would give an even more holistic view, impact, and feasibility of different refurbishment scenarios both in environmental and economic terms.

Introduction

The recent 5th Intergovernmental Panel on Climate Change (IPCC) report on climate change lists cities as main contributors to climate change. Apart from the consumption of energy in the usage phase of buildings, building materials making up cities are listed as being of high relevance as well (IPCC 2014). Current European building standards already aim for near zero energy buildings by the early 2020s and 2018 for public buildings (EU 2010). What remains is the issue of refurbishment strategies and material usage in the built environment, which is addressed by the United Nations Environment Program (UNEP) Recourse Panel (UNEP 2013) and the European Commission (EC) Resource strategy (EC 2011) that needs to be enforced on the national level as well. The strategy for 2030, which was due for ratification in November 2014, should further

Conflict of interest statement: The authors have no conflict to declare.

Address correspondence to: York Ostermeyer, Department of Civil and Environmental Engineering, Chalmers University of Technology, Sven Hultins gata 8, 412 96 Gothenburg, Sweden. *Email*: york.ostermeyer@chalmers.se, *Web*: www.chalmers.se/en/staff/Pages/york-ostermeyer.aspx

DOI: 10.1111/jiec.12616

Editor managing review: Seiji Hashimoto

Volume 22, Number 4

stress the needs of energetic refurbishment, complementing it with a focus on construction materials and embodied emissions and therefore adding another dimension to the discussion.

Cities and governments need to address both aspects and develop economically feasible pathways to refurbish the existing building stock. This need is addressed, among others, by building stock models (BSMs) that aim to describe the effect of refurbishment strategies. These models allow the identification of the impact of refurbishment strategies on a city or even country level in different dimensions (economic and environmental). In contrast to the evaluation of refurbishment strategies on a building level, a BSM can describe the possible synergies or conflicts of different strategies between the energy supply and energy demand side on a larger scale.

So far, BSMs have mainly been developed based on representative building clusters. This includes the model developed by the authors (Wallbaum et al. 2009, 2010; Heeren et al. 2013; Jakob et al. 2013) as well as other models. An overview of different BSMs in the residential sector is given in Kavgic and colleagues (2010). These models focus on modeling the energy consumption of the building stock as well as the related greenhouse gas (GHG) emissions (cf. table 2 in Kavgic et al. [2010]), but neglect the consumption of construction materials and embodied emissions. They are therefore not advanced enough yet to model the total impact of both the usage phase and the material consumption of the built environment. Existing BSM model refurbishment measures simply through changing the thermal transmittance (U-value) of the building components and thereby models the related reduction of the specific heat demand of the building. The actual possible refurbishment measures that are applied, depending on the initial makeup of the different building components, are not considered, meaning also the materials used are unknown.

In Jakob and colleagues (2014), the authors extended their existing model to include embodied energy and emissions by assigning typical construction makeups to newly constructed buildings and refurbishments based on typical market shares. The focus, however, was modeling the embodied impact of new construction and the refurbishment was only modeled very coarsely, without considering the makeup of the underlying building elements in great detail. This limits the applicability as it does not contain any information on the makeup of the building components of the current building stock nor does the setup of the model allow the differentiation of certain building components due to changing building practices over the years. The model framework of Jakob and colleagues (2014) therefore does not allow the modeling of component-specific refurbishment scenarios.

This article introduces a first step to a next generation of component-based building inventories to be used in building stock modeling. Based in the research framework NRP66 of the Swiss National Science Foundation (SNSF) to address the optimal usage of wood as a resource in Switzerland (SNSF 2012), the focus lies on the usage of wood-based materials in the built environment, specifically the use of wood as a building material in refurbishment scenarios. However, the general approach described can be applied on a wider scale as the generated data set can be expanded to cover all material usage in the built environment. This article describes a way to structure and collect building data in a form usable by building stock models by including building-component–specific information. The database generated improves on past data sets in several ways, providing component-based data on refurbishment options and interfaces to the assessment of embodied impact as well as economic calculations. This includes refurbishment options that either use conventional or wood-based materials. The database will therefore allow the modeling not only of refurbishment effects on the energy consumption of buildings in their usage phase, but also on material input and waste flows, currently with a focused application of wood as a resource. The strengths of this new component-based database are demonstrated in two example applications.

The database is published alongside this article and publicly available as supporting information S1, S2, and S3 available on the Journal's website. It is aimed to be continuously updated in future research projects, thus improving its resolution. This article is divided into four parts. First, the structure and differentiation of the proposed component-based building inventory are described. Then, the advantages of the proposed approach are shown based on applications of the database developed in the NRP66 project. Finally, an outlook on a further development of the database is given.

Method

The following methodology describes how to cluster buildings in a building inventory in order to define refurbishment options in a component-based refurbishment scenario database (cf. figure 1). The structure of the database was chosen based on the need to cluster the building stock. The building clusters reflect the dominating building technologies and preferences of a given building period. The first main structure of the database therefore are age groups that are chosen based on building technologies and are in line with commonly used building assessment report methodologies. The second main structure of the database is based on the building types. The generated clusters based on building type and age are then divided according to their main building components. These are further structured according to the main material of the building construction system. Due to the diversity of construction systems, the clustering of building typologies inherently means that certain simplifications need to be made and not all building technologies will be reflected in the database. However, by relying on established literature (SFOE 2001; Amtmann and Gross 2011) as well as involving construction experts to develop and verify the chosen refurbishment options, the developed database yields a reliable basis to be used in building stock modeling. The database aims to provide the detail needed for applying feasible refurbishment options but not more, neglecting diversification for example of the type and heat

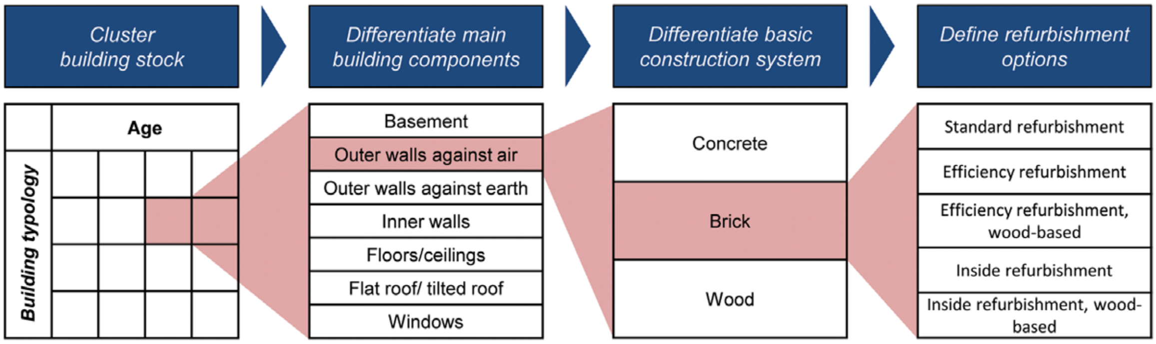


Figure 1 Schematic overview of the structure of the component-based database.

conductivity of brick in existing structures. The database was implemented in MS EXCEL due to the ease of sharing and use of the database.

Age Clusters

The buildings are clustered according to their construction year. The resulting age clusters (shown in figure 2) were chosen to be in line with the ones commonly used by other sources (e.g., BPIE 2011; TABULA [IWU 2012]) and also match with periods that are characterized by typical construction systems. Especially relevant was the alignment with existing assessments of energy performance of the Swiss building stock (Wallbaum et al. 2009, 2010; AWEL 2014) in order to have a working interface with such works and enable building stock models that use the generated database to adjust their calculations.

Past reports (AWEL 2014; Dettli et al. 2007) have demonstrated that there is a clear alignment between building age and energy consumption (cf. figure 2). This is directly related to the building technologies and materials applied. In many countries, it also has to be reflected based on social circumstances, like the urgent need for a large number of shelters, which then is accounted in industrialized building programs such as the million house program in Sweden, often the buildings have a lower quality and higher resulting energy consumption in the usage phase (Johansson 2012). Last, building age is an information that is available in most regions on a geographical information system (GIS) level and the connection of this information to typical building technologies, which is much more challenging to get hold of on a GIS level, is a main asset of the database generated.

In order to be used in building stock modeling, where newly constructed buildings are also modeled, the database also includes age clusters for future buildings. These clusters are designed to represent current and expected future building practices, especially in the development of the energy efficiency standards.

Building Typologies

The building inventory should further be differentiated according to three main building types: single/double-family houses, multifamily houses, and office buildings. These three building types cover about 72%, a major share of the total heated floor area of the building stock of Switzerland (Wüest & Partner 2014). Further, other typologies tend to be too diverse in their makeup to be clustered easily. The database, however, could be expanded to also include other building types, such as schools or hospitals, to gather a more complete view of the building stock. The chosen typology also matches the ones used by most other stakeholders (e.g., Eurostat 1997; SIA 2009; Wüst & Partner 2014) and are reflected in existing GIS data sets (SFOS 2012), allowing an easy connection of the generated database with exiting GIS ones.

Building Components

The building clusters are further differentiated into their main building components according to the following structure that is taken from the definitions of the norm EN 18 599 (DIN 2007):

- Basement (floor against earth)
- Outer walls against air (all outer opaque elements above ground)
- Outer walls against earth (all outer opaque elements below ground)
- Inner walls (interior walls separating rooms or apartments)
- Floors/ceilings (all inner floors between building stories)
- Flat roof/tilted roof (flat roof being tilt <15%; tilted roof being tilt >15%)
- Windows (all transparent elements above ground safe doors)

These building components reflect the majority of the envelope of buildings and, therefore, the envelope related aspects of energy consumption via transmission losses. Furthermore, the main components inside the building (floors/ceilings and inner walls) are listed as well, as they contribute significantly to the material usage in buildings. Not included are heating, ventilation, and air-conditioning components, such as the heating or ventilation system, nor are any electrical installations considered.

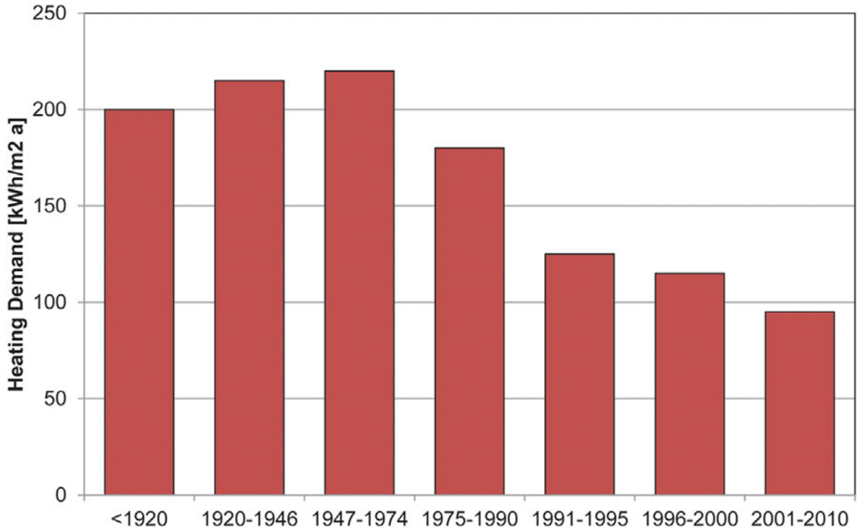


Figure 2 Average energy consumption of buildings in Switzerland according to the age of the Swiss building stock (adapted from AWEL 2014). kWh/m^2 a = kilowatt-hours per square meter per annum.

Basic Construction System

The different building components are further divided according to major building construction systems. The relevant construction systems were differentiated based on typical construction practices according to literature such as SFOE (2001) and Amtmann and Gross (2011). They are differentiated in a level of detail needed to define the major aspects of the refurbishment options. It is relevant whether to have a wood, concrete, or brick wall in order to decide on the refurbishment approach; however, it is not necessarily relevant what kind of brick was used. As not all construction systems are relevant for all building types and age clusters, this is reflected in the data set.

A central aspect of the construction system applied is the thermal mass of the building. Thermal mass allows a building to store heat energy in its building components and thereby be more robust to overheating as well as being able to cover short heat demands via the stored heat energy rather than immediately needing active heating via a heating system. Thermal mass has been proven to especially relevant for low insulated buildings and buildings relying highly on solar gains in moderate or cold climate, especially in the changing seasons (Hacker et al. 2008; Heeren and Hellweg 2014).

The database provides lightweight (low thermal mass, generally wooden buildings) as well as massive (high thermal mass, generally brick or concrete buildings) construction systems, and the further differentiation into building components allows for the generation of medium thermal mass by combining massive and lightweight components, also called hybrid solutions. This rather new phenomenon is aiming to get the best of both worlds by mixing basic construction systems (Yeoh et al. 2011).

The thermal mass (low, medium, high) is information that is generally available for all buildings, which have an energy certificate of any sort as it directly affects its energy demand. Based on building age, typology, and basic construction system/thermal mass, an engineer can make an educated guess on the most feasible makeup of the building components as they follow a logic due to structural (stability) and building constructive demands (how to fulfil fire safety, rain tightness, and so on).

Refurbishment Options

Based on the structure of the building inventory described above, the developed data set effectively lists necessary material input and waste output for different refurbishment options for each building component as well as the initial and resulting makeup of the component. Definitions of the refurbishment options were based on the needs of the NRP66 framework that this work is a part of. Because of this, the refurbishment options focus on solutions that make use of wood-based materials as well as established solutions to compare them to. The data set also includes inside measures, both with mineral- as well as wood-based materials, for buildings that are registered as a historical monuments and for which outside modifications are not allowed. The inside refurbishment options determine what is technically and economically (due to the loss of space inside) possible, the database does therefore not include different efficiency levels for the inside insulation options. All refurbishment options are defined in a way that they are compatible within the same refurbishment scenario (i.e., the wood-based refurbishment of a certain wall type is compatible with the option from the same scenario for the roof or window). A further differentiation of refurbishment options using nonwood materials was not included in the data set. Therefore, the current structure of the refurbishment options does not constitute a complete overview of all possible options. However, additional refurbishment options can be added in the future to complete the data set.

Based on these requirements, five different refurbishment options were developed for each building construction system of each building component, which can be characterized according to table 1.

All refurbishment options are created for each building component of each age cluster, building typology, and construction system. Exceptions are the building components between heated areas (inner walls, ceiling between heated areas), for which only a differentiation between wood and non-wood-based refurbishment options are specified. The refurbishment options were defined based on typical construction practices according to literature such as SFOE (2001) and Amtmann and Gross (2011) as well as in joint cooperation between the authors and experts from the Fachagentur Holz in Germany (experts in agency wood, which are based on experiences in research and realization of refurbishments). Table 2 shows example refurbishment options as it is listed in the database for the building component outer wall against air with the basic construction system brick for the case building type single-family house and the age cluster 1947–1974. The described refurbishment options are insofar plausible as they can also be linked to options listed in SFOE (2001) as is shown by the related reference numbers in table 2. However, the current state of the data set is strongly defined by the needs of the NRP66 project in both the structure (i.e., the defined refurbishment scenarios) and the level of detail of the data contained (i.e., focus on wood-based materials). Ways to further develop the database and improve the quality of the data in order to make it more widely applicable is therefore discussed in the *Discussion and Outlook* section at the end of this article.

Boundary Conditions for Refurbishment Options

The functional unit for all materials contained in the data set was defined as 1 square meter (m^2) of the surface area of the building component. The material input and waste output for the different refurbishment options are normalized accordingly and are described based on the layer thickness in the component makeup. Further, the refurbishment options are normalized based on their thermal insulation properties, meaning all components refurbished according to the same scenario (e.g., the standard scenario) have identical U-value afterward, regardless of their former condition. Moreover, all refurbishments assume an intact component as a basis. Therefore, no preliminary repairs of the structural components are accounted for. All refurbishment options were designed according to:

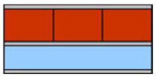
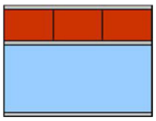
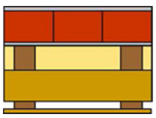
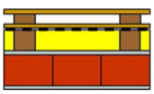
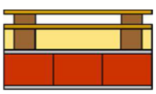
- Building law (they are legally valid) (SIA 2009; EnDK 2008)
- Building physical characteristics (they adhere to hygrothermal aspects)
- Market practices (they use established building constructive solutions as shown in SFOE [2001] or CRB [2011])

The data set not only includes component makeups for future age clusters, but is also designed to allow for the generation of scenarios that include refurbishments conducted in the future—very likely using insulation with better thermal insulation properties. Applying a material with lower thermal transmission properties reduces the insulation thickness as well as the use of materials that depend on the insulation layer (e.g., battens in a ventilated wall makeup). In order to be able to substitute thermal insulation materials, a generic material with a harmonized thermal resistance value (Lambda) of 0.040 watts per meter-kelvin (W/(K·m)) is used. Thermal insulation thickness is determined based on that value. The use of insulation materials as well as materials dependent on the insulation thickness for each refurbishment option can therefore easily be adapted according to the actual Lambda value of the insulation material. An insulation material with a lower Lambda value would therefore result in a reduction of the

Table 1 Characteristics of the different refurbishment options distinguished in the data set for each construction system, age cluster, and building type

Refurbishment option	*Description*
Standard refurbishment	Standard refurbishment option according to current trends and legal requirements with a focus on cost efficient solutions. The resulting U-value of the refurbished building components lies between the legal minimum (EnDK 2008) and the MINERGIE standard.
Efficiency refurbishment	Advanced refurbishment reflecting stricter energy efficiency standards such as Passivehouse or MINERGIE P. In addition to the increased insulation thickness, this refurbishment option also lays a focus on the minimization of thermal bridges.
Wood-based efficiency refurbishment	The same refurbishment option as the one above energetically (U-value and thermal bridges), however with a focus on the use of wood-based products wherever possible and economically feasible, i.e., cost-efficient.
Inside refurbishment	Refurbishment option for protected buildings, which applies only inside measures. The extent of the refurbishment option is limited by the hygrothermal properties of the insulation materials used and takes into the increased thermal bridges.
Wood-based inside refurbishment	The same refurbishment option as the one above energetically (U-value and thermal bridges), however with a focus on the use of wood-based products wherever possible and economically feasible, i.e., cost-efficient.

Table 2 Structure of component-based data contained in the database, showing the initial makeup and refurbishment options for the building component outer wall against air, construction system brick, building typology single-family house, age cluster 1947–1974

Option	*Component makeup*	*Material makeup*	*Waste material*	*New material*
Initial makeup		■ Inside plaster 20 mm ■ Brick wall 290 to 450 mm ■ Outside plaster 20 mm		
Standard refurbishment (Ws01)		■ Inside plaster 20 mm ■ Brick wall 290 to 450 mm ■ Outside plaster 20 mm ■ Composite Insulation 100 mm ■ Outside plaster 15 mm	- None	+ Composite insulation 100 mm + Outside plaster 15 mm
Efficiency refurbishment (Ws01)		■ Inside plaster 20 mm ■ Brick wall 290–450 mm ■ Outside plaster 20 mm ■ Composite insulation 300 mm ■ Outside plaster 15 mm	- None	+ Composite insulation 300 mm + Outside plaster 15 mm
Wood-based efficiency refurbishment (Ws02)		■ Inside plaster 20 mm ■ Brick wall 290–450 mm ■ Outside plaster 20 mm ■ Wooden beam 160 mm [10%] ■ Wood fiber insulation 160 mm [90%] ■ Wood fiber board 200 mm ■ Substructure 30 mm ■ Facade 25 mm	- None	+ Wooden beam 160 mm [10%] + Wood fiber insulation 160 mm [90%] + Wood fiber board 200 mm + Substructure 30 mm + Facade 25 mm
Inside refurbishment (Ws03)		■ Gypsum plaster board 12.5 mm ■ Vapor barrier ■ Wooden beam 100 mm [15%] ■ Insulation 100 mm [85%] ■ Inside plaster 20 mm ■ Brick wall 290–450 mm ■ Outside plaster 20 mm	- None	+ Gypsum plaster board 12.5 mm + Vapor barrier + Wooden beam 100 mm [15%] + Insulation 100 mm [85%]
Wood-based inside refurbishment (Ws03)		■ Oriented strand board (OSB)-board 16 mm ■ Wooden beam 100 mm [15%] ■ Wood fiber insulation 100 mm [85%] ■ Inside plaster 20 mm ■ Brick wall 290–450 mm ■ Outside plaster 20 mm	- None	+ OSB-board 16 mm + Wooden beam 100 mm [15%] + Wood fiber insulation 100 mm [85%]

Note: The reference number in brackets link the refurbishment options to options listed in SFOE (2001).
mm = millimeters.

necessary insulation thickness to reach the same efficiency standard (U-value) as well as the materials that depend on the insulation thickness (e.g., substructure in a ventilated façade). The drawback of this approach is that some insulation materials are only available in certain dimensions. While the insulation thickness contained in the data set is based on available market products, the resulting thickness, when adapted with a different Lambda value, may not be for every insulation material.

While the material usage of each refurbishment option is normalized based on the functional unit (the surface area of the building component) and according to their thermal insulation performance (the Lambda value of the insulation material), they differ according to other properties such as:

- Sound protection
- Fire resistance
- Robustness against vandalism and weathering
- Structural capacity

The refurbishment options are designed so that all of these aspects are in line with the legal requirements by checking the relevant norms. The different base conditions, however, result in different levels of performance (e.g., a massive wall refurbished according to standard scenario will have a different level of sound protection compared to a wooden wall refurbished according to the same scenario—however, both will have the same U-value as described above). Therefore, the building component properties mentioned above are considered outside the system boundaries of the refurbishment database described in this article.

Example Applications of the Data Set

In the following section, the advantages of a component-based building inventory approach to modeling the environmental impact of building refurbishments are demonstrated based on two examples using the database generated in the NRP66 framework. The following two examples describe the possible applications of the data set for an evaluation of refurbishment scenarios on a building component and on a building level. The application of the data set, in combination with a building stock model for a building stock wide analysis, is discussed in the *Discussion and Outlook* section.

Impact Assessment Method

The developed data set effectively list necessary material input and waste output for different refurbishment options on a Swiss scale with a focus on wood. In combination with a life cycle inventory (LCI) data set, for example, from ecoinvent v3.1 (2014), the environmental impacts of the different refurbishment options can be described. Table 3 lists the materials used in the life cycle assessment (LCA) calculations for the evaluation of the refurbishment options and their impacts for the indicators' global warming potential (GWP), cumulative energy demand (CED total) and ecological scarcity according to ecoinvent v3.1 (2014). The assessment carried out for the following two examples only includes the added new materials of the refurbishment options, as the materials of the initial building component makeup are already built. They were therefore considered as sunk environmental costs and outside the system boundary as they are the same for all refurbishment options.

The impact assessment on the database can be used on its own to evaluate different refurbishment options on a component basis. Based on the initial makeup of the component, the produced waste materials and new material input can be evaluated for each refurbishment option considered. The component-based evaluation of the material usage and the related environmental impact for the refurbishment options is demonstrated on the example of the brick wall described in table 2.

In order to make a statement about the overall environmental impact of a refurbishment option, the usage phase of the building has to be considered as well. For this purpose, a second building-based evaluation was performed for an exemplary single-family house building with a heated floor area of 158 m^2. In order to be in line with the other examples presented in this article, the example building was chosen as a single-family house from the age cluster 1947–1974. The specifications of the example building are described in table 4. The embodied impact was calculated for each component individually analogous to the component-based evaluation above, using the LCI data described in table 3. The evaluation of the refurbishment is limited to the refurbishment of the components in the building envelope, which form the insulation perimeter and the interior walls, the basement walls, and floor, are therefore excluded from the evaluation. In order to be able to assess the embodied impact of the material usage compared to the building usage phase, the embodied impact is allocated over an assumed lifetime of each component. The component lifetimes are assumed according to standard lifetimes described in SIA (2010). The space heating demand during the usage phase is calculated according to the Swiss norm SIA 380/1 (SIA 2009) using standard values from the same norm. The overall building lifetime was chosen as 60 years. The space heating demand is covered by an oil boiler (see table 3).

Component-Based Evaluation of Refurbishment Options

Figure 3 shows the resulting material use and the related environmental impact per m^2 wall area of the example described in table 2. Due to the differences in the U-value of the refurbishment options, also the resulting material usage and environmental impact differs greatly. However, when comparing the wood-based option with the corresponding non-wood-based option with the same efficiency standard, figure 3 shows that the wood-based option has a significantly higher material usage. This is mostly due to the different component makeup of the wood-based option. The wood-based options require

Table 3 Data sources for LCI of the building components from ecoinvent v.3.1 (2014) used in the application examples of the data set

Process/product	*Reference product in ecoinvent v3.1 (2014)*	*Reference unit*	*Density [kg/m³]*	*GWP [kg CO_2-eq]*	*CED total [MJ]*	*Ecological scarcity [Pt]*
Hardwood board	Planning, board, hardwood, kiln dried, CH	m^3	700	53.5	22,349.9	260,314.7
Softwood beam	Planning, beam, softwood, kiln dried, CH	m^3	500	45.6	16,755.3	213,211.4
Oriented strand board (OSB)-board	Oriented strand board production, RER	m^3	650	266.9	23,815.9	515,144.6
Sarking membrane	Fleece production, polyethylene, RER	m^3	920	2,375.2	88,077.6	2,304,432.1
Tiles	Roof tile production, RER	m^3	1,700	586.2	6,874.2	465,240.5
Plaster floor	Cement cast plaster floor production, CH	m^3	1,850	314.7	2,191.9	319,166.2
Gypsum board	Gypsum plasterboard production, CH	m^3	850	137.6	4,012.0	265,021.4
PUR insulation	Polyurethane production, rigid foam, RER	m^3	30	123.3	3,068.4	145,242.5
Extended polystyrene (EPS) insulation	Polystyrene foam slab production, RER	m^3	30	128.0	3,210.7	114,007.2
Rock wool insulation	Rock wool production, CH	m^3	120	112.5	2,141.7	192,737.3
Soft wood fiber insulation	Fiberboard production, soft, from wet processes, CH	m^3	55	41.6	2,010.6	70,809.4
Wood fiberboard insulation	Fiberboard production, soft, from wet processes, CH	m^3	110	83.1	4,021.3	141,618.8
Window frame wood	Window frame production, wood, U = 1.5 W/m²K, RER	m^2	—	140.7	6,056.4	375,366.8
Double glazing	Glazing production, double, U < 1.1 W/m²K, RER	m^2	—	27.7	491.3	42,096.5
Triple glazing	Glazing production, triple, U < 0.5 W/m²K, RER	m^2	—	45.9	819.5	65,318.4
Interior plaster	Cover plaster production, mineral, CH	m^3	1,200	125.5	2,347.2	232,112.9
Exterior plaster	Base plaster production, CH	m^3	1,400	316.0	2,711.1	313,319.7
Particle board	Particle board production, cement bonded, RER	m^3	1,800	864.3	9,243.9	761,375.4
Vapor barrier	Polyethylene production, high density, granulate, RER	m^3	920	1,738.7	71,115.0	1,421,614.7
Heating oil	Heat production, light fuel oil, at boiler 10 kW, non-modulating, CH	MJ	—	0.1	1.4	71.4

Note: GWP = global warming potential (Myhre et al. [2013], GWP 100a); CED = cumulative energy demand total, ecological scarcity 2013.
LCI = life cycle inventory; W/m²K = watts per square meter-kelvin; kW = kilowatts; m^3 = cubic meter; m^2 = square meter; MJ = megajoule; kg/m^3 = kilograms per cubic meter; kg CO2-eq = kilograms carbon dioxide equivalent; Pt = points.

a static structure (i.e., the supporting wooden beams), while extended polystyrene (EPS) insulation layer in the nonwooden refurbishment option is simply glued to the outside of the existing structure. The difference in the total material usage between the wood-based and the non-wood-based option is significantly lower when comparing the two indoor refurbishment options, which are more comparable in their makeup (cf. table 2).

Table 4 Building parameters for the example building and its component-based refurbishment options, building typology single-family house, age cluster 1947–1974

	Basement ceiling	*Outer walls*	*Windows*	*Tilted roof*
Basic construction system	Concrete	Brick	Wood	Wood
Component surface area [m^2]	79.0	133.3	59.8	94.8
Assumed lifetime of refurbishment [years]	40	30	30	40
U-values: [W/m^2K]				
-Initial makeup	0.56	0.98	1.7	0.74
-Standard refurbishment	0.23	0.25	1.3	0.24
-Efficiency refurbishment	0.15	0.12	0.8	0.10
-Wood-based efficiency refurbishment	0.15	0.12	0.8	0.10
-Inside refurbishment	0.15	0.33	1.3	0.24
-Wood-based inside refurbishment	0.31	0.33	1.3	0.24

Note: m^2 = square meter; W/m^2K = watts per square meter-kelvin.

The different U-values of the refurbishment options have a similar effect on the resulting environmental impact, especially when comparing the standard and efficiency options. Comparing again the wood-based options with the corresponding non-wood-based options of the same efficiency standard, the first shows a higher cumulative energy demand compared to the non-wood-based options, while the contrary is true for the GWP. The lower global warming impact for the wood-based materials due to the fact that the ecoinvent database used does not include biogenic GHG emissions. The difference between the two types of refurbishment differs, however, for the ecological scarcity indicator, where for the two efficiency options, the nonwood option shows a lower impact, while for the two inside insulation options, the opposite can be observed. This effect can mainly be attributed to the significantly higher material use of the wood-based efficiency option compared to the nonwood option, which offsets the generally lower impact of the wood-based products in terms of ecological scarcity. Across the different refurbishment options, the results in figure 3 show that the major contribution to the environmental impact of the scenarios stem from the insulation materials.

Building-Based Evaluation of Refurbishment Options

Apart from a component-based evaluation of different refurbishment scenarios, the data set can also be used for an evaluation on the building level. This allows not simply to evaluate the material use and produced waste materials of the different refurbishment options as was done in the component-based analysis above, but to compare the embodied impact of these options with the environmental impact of the space heating demand of the use phase.

The material and life cycle impact assessment (LCIA) results of the example building-based evaluation are shown in figure 4. The material usage includes the generation of waste materials (i.e., the materials removed during the refurbishment) by the refurbishment options, which were missing in the component-based evaluation as the chosen example generated no waste materials in the refurbishment options (cf table 2). Similarly, according to the component-based evaluation, the wood-based refurbishments are more material intensive compared to their nonwood counter parts. Additionally, figure 4 shows that the wood-based efficiency scenario also generates more waste products compared to the other options as more of the initial makeup of some components are replaced with new materials. The differences in the environmental impact between the different refurbishment scenarios and indicators shown in figure 4 are similar in terms of the embodied effect compared to the component-based evaluation. However, the impact of the space heating demand of the use phase outweighs the embodied material impact, especially for the standard and inside refurbishment options. The space heat demand of the wood-based inside insulation scenario is slightly higher than its non-wood-based counterpart. This stems from the fact that the inside insulation option for the building component wall only considers the added materials of the refurbishment options; this analysis skews toward a higher impact of the space heating demand as the impact of the initial building components was not included. Nevertheless, figure 4 also shows that the relative share of the material impact is higher for the more efficient scenarios.

This analysis can be scaled up by combining the developed database with a building stock model in order to evaluate the material usage and environmental impact of refurbishment scenarios on a national scale as is discussed in the following outlook section.

Discussion and Outlook

The results of the two example applications show how the generated data set can be used on its own to evaluate the generated material flows (input as well as output) and their environmental impact on refurbishment processes on a component or building level. This makes it possible to optimize the refurbishment strategies from a material perspective (as in the NRP66 project with a focus on wood usage) both on the input (sourcing of materials) and the output side (generated waste materials).

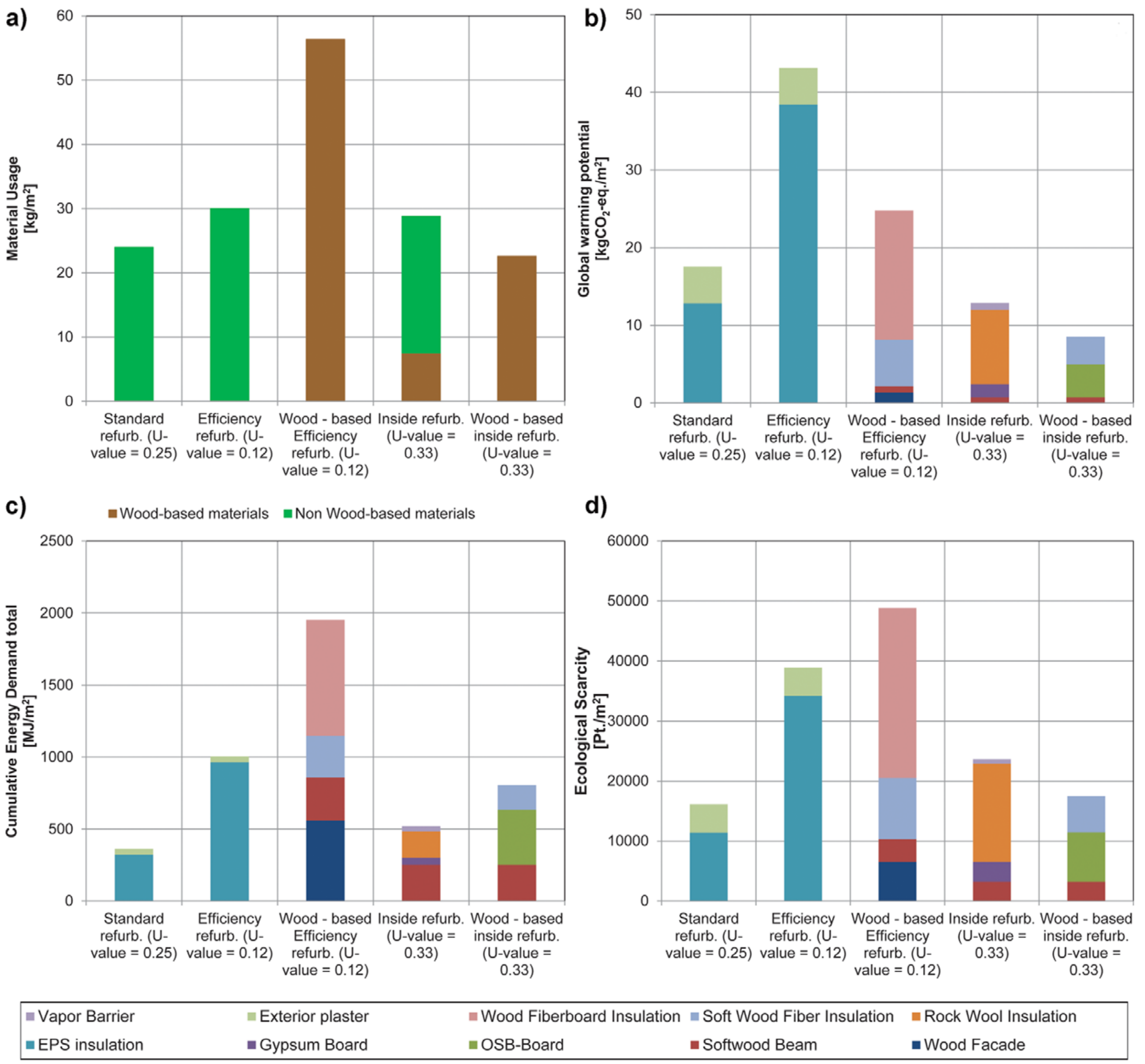


Figure 3 Material use and its environmental impact per m^2 component surface area of the efficiency refurbishment (refurb.) options (single-family house/outer wall/system brick/age cluster 1947–1974). (a) Material usage; (b) cumulative energy demand total; (c) global warming potential (Myhre et al. [2013], GWP 100a); and (d) ecological scarcity 2013. LCIA data shown in table 3, based on ecoinvent v3.1 (2014). *Notes:* U-value = thermal transmittance; EPS = extended polystyrene; OSB = oriented strand board. m^2 = square meters; LCIA = life cycle impact analysis; kg/m^2 = kilograms per square kilometer; kg CO_2-eq/m^2 = kilograms carbon dioxide equivalent per square meter; MJ/m^2 = megajoules per square kilometer; Pt./m^2 a = points per square meter.

The demonstrated example analysis was carried out in a way that can also be done on a broader scale using a building stock model. Combining the data set with a building stock model will therefore allow this analysis to be scaled up, enabling the evaluation of material flows on a city, regional, or national level. Further, using the data set in a component-based building stock model makes it possible to generate a consistent evaluation of the environmental impact of the building stock during the construction, disposal, and the use phase. Moreover, by differentiating between input and output materials, a more accurate temporal allocation of the environmental impact of the material production and disposal to the beginning and end of the use phase in the building respectively is possible. By applying a dynamic LCA method in the building stock model, this would make it possible to more accurately account for the time of the emissions. Levasseur and colleagues (2010) show that this can have a significant effect on the GWP of certain products. Compared to common building stock models, this creates a more holistic picture of the environmental impact of the building stock and makes it possible to assess which energy efficiency

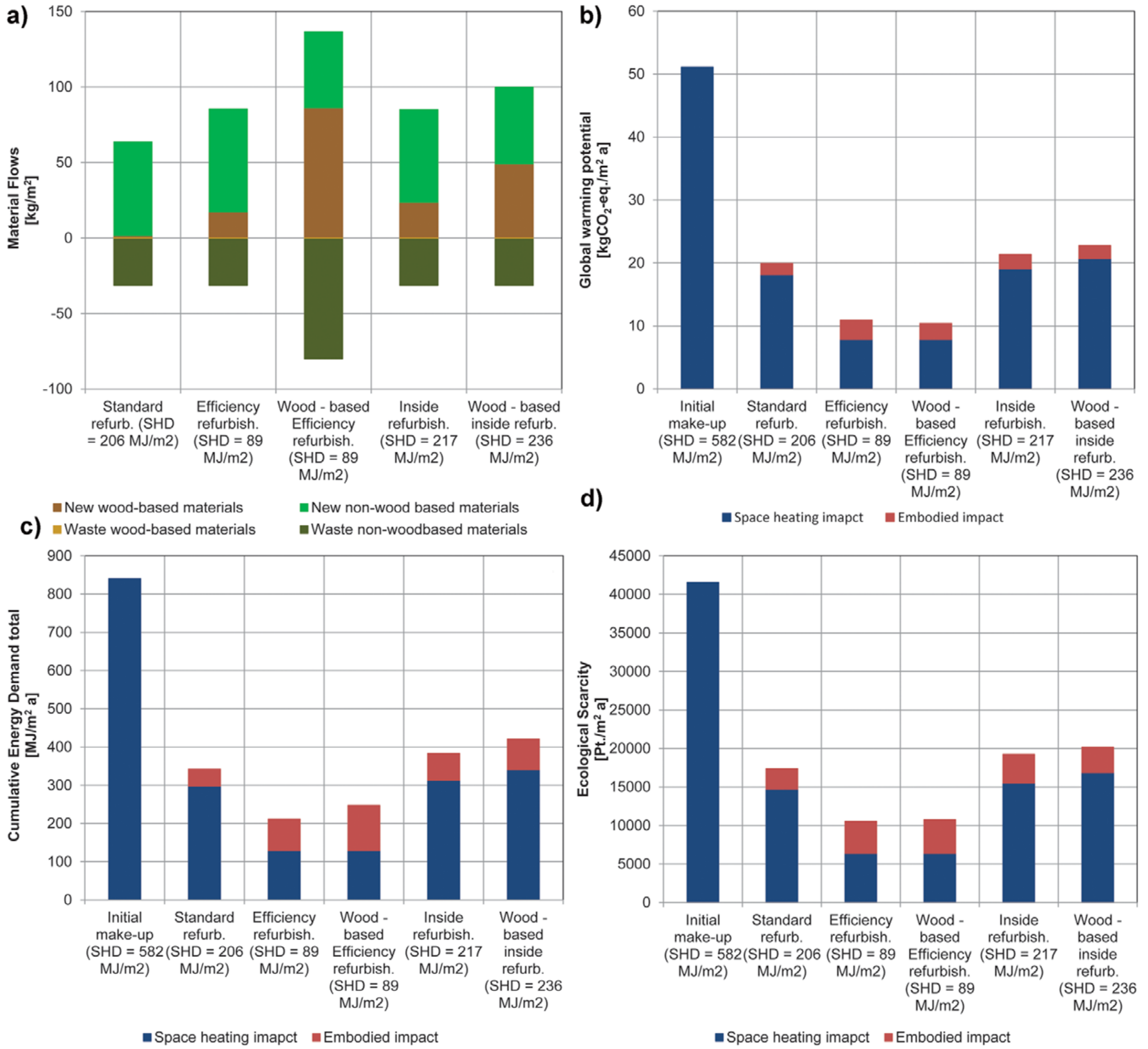


Figure 4 Material flows and environmental impact (only considering new materials) per m^2 heated floor area and year for different refurbishment options for the exemplary single-family house described in table 4, age cluster 1947–1974. The resulting space heating demand (SHD) of the different refurbishment options is shown in brackets. (a) Material flows; (b) cumulative energy demand total; (c) global warming potential (Myhre et al. [2013], GWP 100a); and (d) ecological scarcity 2013. LCIA data shown in table 3, based on ecoinvent v3.1 (2014). Overall building lifetime = 60 years, component lifetimes according to table 4. *Note:* SHD = space heating demand. m^2 = square meters; LCIA = life cycle impact analysis; kg/m^2 = kilograms per square kilometer; kg CO_2-eq/m^2 a = kilograms carbon dioxide equivalent per square meter per annum; MJ/m^2 a = megajoules per square kilometer per annum; Pt./m^2 a = points per square meter per annum.

standards to aim for on a country level not just taking into account the use phase, but also the necessary material use and embodied impact.

The developed data set is currently defined by the needs of the NRP66 project in both the structure of the defined refurbishment options and the data contained material data. It gives therefore a high resolution concerning wood-based make-ups and materials, but lacks in a differentiation of the non-wood-based materials. For a broader assessment, the resolution would have to be increased in order to give a more complete overview of the material usage in the building stock. Further, the granularity of the different component makeups could be increased to make even finer distinctions and give a more accurate picture of the building stock. For this reason, the data set is published alongside this article and is freely available in order to make the further development and quality assurance of the data set easier. For this purpose, also an integration of the data set in existing tools, such as the building component catalogue by SFOE (2001), could be considered, which would also increase its applicability.

The data set is structured in a way that further data can be added easily on a component level either to extend the data set with a further differentiation of the refurbishment options or to add to the component-based data. For example, the database could be extended to include representative lifetimes of the different component makeups. Instead of using general component lifetimes, they could be differentiated according to their makeup. Grant and colleagues (2014) show the significance of the assumption of the building component lifetimes and the impact it has on the environmental assessment of buildings. This would therefore make it possible to model the environmental impact of refurbishment strategies in a building stock model in more detail and more accurately.

Further, due to the component-based structure of the data set, it is relatively easy also to include future (innovative) material solutions by replacing the traditional materials in the refurbishment option. This enables one to easily assess the environmental potential of new materials on a broad scale when the data set is used in a building stock model. By extending the data set with specific lifetimes for each component makeup as suggested above, not only the potential of innovative solutions in terms of a lower U-value or lower material usage can be assessed, but also the effect of innovations that prolong the component lifetime. By giving building stock wide information where an innovation could be applied, the data set also facilitates not just assessment of the environmental, but also the market potential of these new material solutions.

The different refurbishment options contained in the data set were defined mainly based on the technical considerations described in this paper. The material choice (e.g., between a wood-based and non-wood-based solution) does, however, depend on many other factors so far not contained in the database, such as costs, labor intensity, as well as preferences of the different stakeholders (Knoeri et al. 2011). Combining the data set with an aligned economic model would therefore be a natural next step. The data set is generated in a way that prices as well as labor intensity can be added just as easily as a component-specific lifetime, which would allow further assessment of the different refurbishment strategies. Next to the considered limitations in terms of material usage, this would make it possible to assess the economic and labor costs of the different scenarios and therefore give a more holistic overview of the impact and feasibility of different refurbishment scenarios both in environmental and economic terms.

Acknowledgments

We thank the experts from the Fachagentur Holz for their valuable input when setting up the database.

Funding Information

This work has been funded by the Swiss National Research Program grant "Resource Wood" NRP 66 (project no. 136612).

References

Amtmann, M. and M. Groß. 2011. Eine Typologie österreichischer Wohngebäude [A typology of Austrian residential buildings], report within the TABULA project. Vienna: Austrian Energy Agency.

AWEL (Office for Waste, Water, Energy and Air). 2014. *Energiekennzahlen Wohnbauten* [Energy data residential buildings]. Zürich, Switzerland: Baudirektion Kanton Zürich, Abteilung für Energie.

BPIE (Buildings Performance Institute Europe). 2011. *Europe's buildings under the microscope—A country-by-country review of the energy performance of buildings*. Brussels: Buildings Performance Institute Europe (BPIE), October.

CRB (Swiss Center for Construction Rationalization). 2011. *Elementarten-Katalog EAK—Ennergiekennwerte* [Component catalogue – Energy indicators]. Schweizerische Zentralstelle für Baurationalisierung. Vol. 2011-04. Zürich, Switzerland: CRB.

Dettli, R., S. Bade, A. Baumgartner, and M. Bleisch. 2007. *Vorstudie zur Erhebung von Energiekennzahlen von Wohnbauten* [Pre-study for survey of energy indicators for residential buildings]. Bern, Switzerland: Eidgenössisches Department für Umwelt, Verkehr, Energie und Kommunikation UVEK, Bundesamt für Energie.

DIN (German Institute for Standardization). 2007. 18599—Energy efficiency of buildings—Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting. *Beuth, Berlin* 2. Germany: German Institute for Standardisation.

EC (European Comission). 2011. *Roadmap to a resource efficient Europe*. COM COM Annex. Brussels: European Comission, 20 September.

ecoinvent 3.1. 2014. Ecoinvent data version 3.1. Dübendorf, Switzerland: Swiss Center for Life Cycle Inventories. www.ecoinvent.ch. Accessed 15 March 2016.

EnDK (Conference of Cantonal Energy Directors). 2008. *Mustervorschriften der Kantone im Energiebereich (MuKEn)* [Sample energy regulations of the cantons]. *Ausgabe 2008*. Bern, Switzerland: Konferenz Kantonaler Energiedirektoren, 4 April.

EU (European Union). 2010. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*. Brussels: EU, June.

Eurostat. 1997. *Classification of Types of Constructions (CC)*. Luxembourg: Eurostat, Unit D1.

Grant, A., R. Ries, and C. Kibert. 2014. Life cycle assessment and service life prediction: A case study of building envelope materials. *Journal of Industrial Ecology* 18(2): 187–200.

Hacker, J. N., T. P. De Saulles, A. J. Minson, and M. J. Holmes. 2008. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings* 40(3): 375–384.

Heeren, N. and S. Hellweg. 2014. Influence of construction material choice and design parameters on greenhouse gas emissions of buildings. In World Sustainable Building Conference SB14, 28–30 October, Barcelona, Spain.

Heeren, N., M. Jakob, G. Martius, N. Gross, and H. 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.

IPCC (Intergovernmental Panel on Climate Change). 2014. *IPCC Fifth Assessment Synthesis Report—Climate Change 2014 Synthesis Report*. Paris: Intergovernmental Panel on Climate Change (IPCC), November.

IWU (Institute living and environment). 2012. *Typology approach for building stock energy assessment. Main results of the TABULA project*. Darmstadt, Germany: Institut Wohnen und Umwelt, October.

Jakob, M., G. Martin, Y. Ostermeyer, and H. Wallbaum. 2014. *Graue Energie und Graue Treibhausgasemissionen der Neubau- und Erneuerungstätigkeit im Gebäudepark in der Stadt Zürich bis 2050* [Grey energy and grey emissions from new building and refurbishment activities in the building stock of the City of Zürich until 2050]. Zürich, Switzerland: Amt für Hochbauten der Stadt Zürich.

Jakob, M., H. Wallbaum, G. Catenazzi, G. Martius, C. Nägeli, and B. Sunarjo. 2013. Spatial building stock modelling to assess energy-efficiency and renewable energy in an urban context. In Cleantech for Smart Cities & Buildings—From Nano to Urban Scale, 4–6 September, Lausanne, Switzerland.

Johansson, B., ed. 2012. *Miljonprogrammet—Utveckla eller avveckla?* [Million Program-Develop or Discontinue]. Stockholm: Formas.

Kavgic, M., A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic. 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment* 45(7): 1683–1697.

Knoeri, C., C. R. Binder, and H. J. Althaus. 2011. Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling* 55(11): 1039–1050.

Levasseur, A., P. Lesage, M. Margni, L. Deschênes, and R. Samson. 2010. Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology* 44(8): 3169–3174.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, et al. 2013. Anthropogenic and natural radiative forcing. In: *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al. Cambridge, UK: Cambridge University Press.

SFOE (Swiss Federal Office for Energy). 2001. *U-Wert-Berechnung und Bauteilekatalog Sanierungen* [U-value calculation and building component catalogue refurbishment]. Bern, Switzerland: Swiss Federal Office for Energy.

SFOS (Swiss Federal Office for Statistics). 2012. *Merkmalskatalog: Version 3.6* [Attribute catalogue, version 3.6]. Neuchâtel, Switzerland: Swiss Federal Office for Statistics.

SIA (Swiss Society of Engineers and Architects). 2009. *SIA 380/1 Thermische Energie im Hochbau* [Thermal energy in buildings]. SN 520 380/1. Zürich, Switzerland: Swiss Society of Engineers and Architects.

SIA (Swiss Society of Engineers and Architects). 2010. SIA Merkblatt 2032 *Graue Energie von Gebäuden* [Grey energy in buildings]. Swiss Society of Engineers and Architects.

SNF (Swiss National Science Foundation). 2012. National Research Programme NRP 66—Resource Wood. http://www.nfp66.ch. Accessed 16 February 2015.

UNEP (United Nations Environment Program). 2013. City-level decoupling—Urban resource flows and the governance of infrastructure transitions. Working Group on Cities of the International Resource Panel. Nairobi, Kenya: UNEP.

Wallbaum, H., N. Heeren, M. Jakob, M. Gabathuler, N. Gross, and G. Martius. 2009. Gebäudeparkmodell SIA Effizienzpfad Energie Dienstleistungs-und Wohngebäude-Vorstudie zum Gebäudeparkmodell Schweiz—Grundlagen zur Überarbeitung des SIA Effizienzpfades Energie [Building Stock Modell SIA, energy efficiency pathway retail and residential, pre-study for the Building Stock Model Switzerland – fundamentals for updating the SIA efficiency pathway]. Bern, Switzerland: IA Bundesamt Für Energie (BFE), September.

Wallbaum, H., M. Jakob, N. Heeren, N. Gross, and G. Martius. 2010. Gebäudeparkmodell—Büro-, Schul-und Wohngebäude—Vorstudie zur Erreichbarkeit der Ziele der 2000-Watt-Gesellschaft für den Gebäudepark der Stadt Zürich [Building Stock Model – office, school and residential buildings – pre-study for assessing the feasibility of the 2000-watt-society for the building stock of the City of Zürich]. Zürich, Switzerland: Amts Für Hochbauten (AHB) Der Stadt Zürich.

Wüest & Partner. 2014. *Gebäudebestandsentwicklung 1990–2013—Energiebezugsflächen* [Development of the building stock 1990-2013 – energy reference area]. Zürich, Switzerland: Wüest & Partner AG.

Yeoh, D., M. Fragiacomo, M. De Franceschi, and K. Heng Boon. 2011. State of the art on timber-concrete composite structures: Literature review. *Journal of Structural Engineering* 137(10): 1085–1095.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes the developed database for the building typology, single-family house for Switzerland. It contains the makeup for the different components clustered according to building period (BP) and building components as well as different refurbishment options for each building component makeup. Based on the component makeup, it lists the necessary material input and waste output for these refurbishment scenarios. Due to the nature of the research project it is only available in German.

Supporting Information S2: This supporting information includes the developed database for the building typology, offices for Switzerland. It contains the makeup for the different components clustered according to building period (BP) and building components as well as different refurbishment options for each building component makeup. Based on the component makeup, it lists the necessary material input and waste output for these refurbishment scenarios. Due to the nature of the research project, it is only available in German.

Supporting Information S3: This supporting information includes the developed database for the building typology, multifamily house for Switzerland. It contains the makeup for the different components clustered according to building period (BP) and building components as well as different refurbishment options for each building component makeup. Based on the component makeup, it lists the necessary material input and waste output for these refurbishment scenarios. Due to the nature of the research project, it is only available in German.