Tracking Construction Material over Space and Time

Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows

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Summary

Construction material plays an increasingly important role in the environmental impacts of buildings. In order to investigate impacts of materials on a building level, we present a bottom-up building stock model that uses three-dimensional and geo-referenced building data to determine volumetric information of material stocks in Swiss residential buildings. We used a probabilistic modeling approach to calculate future material flows for the individual buildings. We investigated six scenarios with different assumptions concerning per-capita floor area, building stock turnover, and construction material. The Swiss building stock will undergo important structural changes by 2035. While this will lead to a reduced number in new constructions, material flows will increase. Total material inflow decreases by almost half while outflows double. In 2055, the total amount of material in- and outflows are almost equal, which represents an important opportunity to close construction material cycles. Total environmental impacts due to production and disposal of construction material remain relatively stable over time. The cumulated impact is slightly reduced for the wood-based scenario. The scenario with more insulation material leads to slightly higher material-related emissions. An increase in per-capita floor area or material turnover will lead to a considerable increase in impacts. The new modeling approach overcomes the limitations of previous bottom-up building models and allows for investigating building material flows and stocks in space and time. This supports the development of tailored strategies to reduce the material footprint and environmental impacts of buildings and settlements.

Introduction

Construction material has an important influence on a building's total environmental impact, especially when considering energy-efficient buildings where increased amounts of insulation material lead to reduced energy demand (Ramesh et al. 2010; Karimpour et al. 2014; Cabeza et al. 2014). In addition to the amount of material, the type of construction materials also influences life cycle environmental impacts (Heeren et al. 2015).

Construction material flows and stocks have typically been studied by means of bottom-up methods (Bergsdal et al. 2007;

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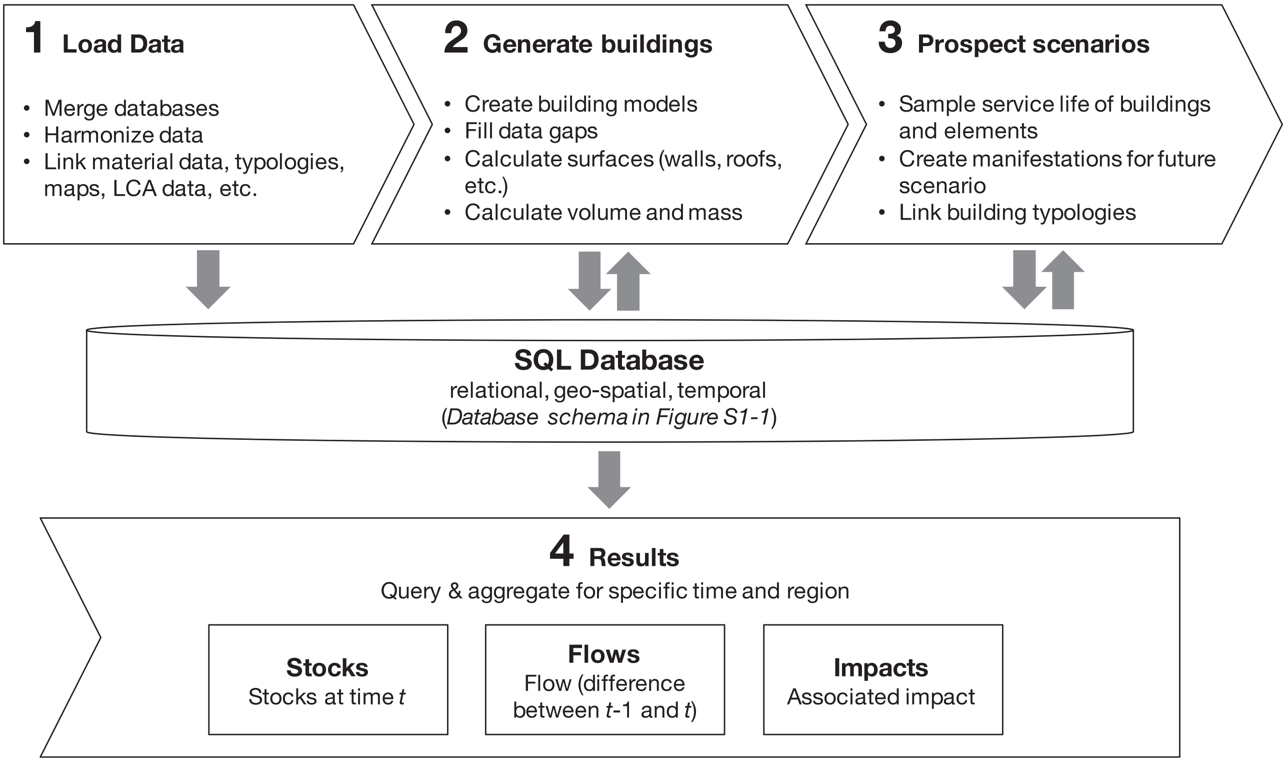

Figure 1 Model procedure overview. LCA = life cycle assessment.

Sartori et al. 2008). D. B. Müller (2006) introduced a comprehensive model with three determinants, describing per-capita useful floor area, concrete intensity, and lifetime, to prospectively model the dynamics of the Norwegian dwelling stock. Several aspects of this model have been developed further in recent years. Sandberg and colleagues (2014b) presented a method that accounts for building stock dynamics in models using a probabilistic and convolution-based algorithm. Furthermore, the use of building archetypes has been adopted by a large number of authors. For instance, Wiedenhofer and colleagues (2015) used an archetype-approach to determine material stocks and flows of buildings and transport networks in the EU25. Kleemann and colleagues (2017) presented a geospatial model to determine material composition of buildings in Vienna, Austria, using sampled case studies and historical geographical information systems (GIS) city maps. Similarly, Tanikawa and colleagues (2015) quantified the evolution of material stocks of buildings and infrastructure by using geo-spatial data, derived from historical city maps. Mastrucci and colleagues (2016) studied demolition waste flows for a city in Luxembourg using geo-spatial data and quantified environmental impacts with the life cycle assessment (LCA) method. Tanikawa and collegaues (2015), Augiseau and Barles (2017), and E. Müller and colleagues (2014) provide a comprehensive overview of the current literature and the different approaches being used for material flow analysis.

In spite of the rich literature regarding building material stock and flow dynamics, the role of building-specific decisions, such as apartment size or material choice, is less understood. With the increasing availability of GIS data and computation power, it has become possible to move beyond the archetype bottom-up approach. However, this has not been applied to national building stocks or prospective models yet. Such an approach would increase accuracy of material stocks quantification and open new perspectives on the temporal and spatial dynamics of building stocks development and material flows. In this paper, we propose a component-based, prospective, and probabilistic modeling approach to quantify the material composition of Swiss residential buildings, which can then be aggregated geographically to model building material stocks and flows of regions. Furthermore, we use scenarios, based on probability sets, to study model sensitivity and policy scenarios. Finally, the material flows are evaluated for their environmental impact by using LCA and considering different environmental impact categories.

Method

Model Overview

As seen in figure 1, the procedure can be differentiated into four individual steps with a geo-spatial SQL database being the model's central element. Step 1: The necessary data were parsed and fed into the database. Two geo-referenced building data sets were merged and matched with each other. Furthermore, other necessary data were copied into the database and interlinked. This included the building typology (Ostermeyer et al. 2017), material data (density, etc.), and impact scores of background processes from Wernet and colleagues (2016). Step 2: The individual buildings models were constructed from the merged database. That means the building elements (walls, windows, roofs, and floors) were determined and their surface areas calculated. Furthermore, the material volume was derived from multiplying surface with material thickness from the building typology. The mass was then calculated by multiplying the volume with material density from the material property database. Step 3: The model generated scenarios and created future buildings. That means service life was sampled for elements and the buildings and elements were linked to a typology. This was done for each building, scenario, and time step individually, resulting in different future manifestations of the same building across the scenarios (2.2 billion in total). Step 4: The model simulation is complete and the database can be queried, by means of SQL commands. Results can be aggregated regionally and a point in time (material stocks). Alternatively, it is possible to query for the change between two time steps, which then corresponds to a material flow. Furthermore, also, other indicators than mass, such as volume or life cycle impact, can be extracted from the database. See also section S1-1.1 in the supporting information S1 available on the Journal's website for more technical information and the database structure.

Processing Geo-Spatial Data

Building data from two national databases were used. The Swiss Federal Register of Buildings and Dwellings RBD (SFSO 2014) contains data of all Swiss residential buildings, such as living area, number of floors, building occupation, and year of construction. The second data source was the swissbuildings3D 1.0 (SB3D) (swisstopo 2010) database. It contains building polygons and building height data (from airborne laser scanning) for individual and groups of buildings of all types (residential, office, and industry). We merged the two building databases based on their geo-location. This had the advantage that we could construct three-dimensional building representations, identify faulty data in either one of the data sets (e.g., height information; see section S1-3.3 in supporting information S1 on the Web), and also obtain building metadata, which was necessary for assigning building typologies. From these three-dimensional representations, we derived the surface of the construction elements, that is, walls, roofs, etc., for every building. Structural elements (foundations, free-standing beams, etc.) and building infrastructure, such as pipes or wires, were neglected. Furthermore, only extensive refurbishment activities were considered, neglecting minor repairs (e.g., plaster replacement or new paint).

Reconciling Data Gaps and Probabilistic Modeling

Due to incomplete and implausible data in the data sources, not all the necessary attributes could be derived directly. The overall procedure for resolving implausible and conflicting data was as follows (refer to section S1-3 and section S1-4 in supporting information S1 on the Web for more details on the procedures for the individual elements):

i. Use data of buildings with similar characteristics (i.e., same year of construction and occupation) within a radius of 300 meters.
ii. If i. yielded less than 10 samples, we used a nation-wide median value of buildings with similar characteristics (i.e., year of construction and occupation).
iii. Sample missing data from an empirical distribution.

The model probed one method after the other, and if none of them was applicable, the building was omitted entirely (e.g., for 53 buildings the construction year could not be determined; see section S1-3.1 in the supporting information on the Web).

$$X \sim F_{s,y_c,bt,t,geo} \tag{1}$$

The sampling procedure of method iii. applied also to other entirely unknown parameters X (e.g., window size, construction type, and roof shape), which could not be determined from the merged database. As illustrated in equation (1), the probability functions F could be dependent on some or all of the following parameters: scenario s, year of construction y_c, building type bt, model time step t (i.e., year when parameter was sampled), and geo-location geo. The functions either applied to buildings b or elements el. The details of database matching and handling of data gaps and conflicts are found in section S1-3 in supporting information S1 on the Web.

As in Heeren and colleagues (2015), the uncertainty functions F are either fitted to empirical values or based on literature values, using normal $\mathcal{N}(\mu,\sigma^2)$, lognormal $\ln\mathcal{N}(\mu,\sigma^2)$, uniform $\mathcal{U}[a,b]$, or Weibull $\mathcal{W}(\lambda,k)$ distributions (section S1-4 in supporting information S1 on the Web).

Determining Building Material Inventory and Flows

Building representation was translated into a building inventory using an architectural typology, developed by Ostermeyer and colleagues (2017). That data set contains past, present, and hypothetical future material inventories for buildings and their elements, along with their market shares. Each construction had custom refurbishment variants, concerning material and energetic standards, which allowed for determining material flow in case of a modification, as described in Ostermeyer and colleagues (2017). Each building was assigned a year of demolition and each element type had a year of refurbishment, which was drawn from an individual probability density function (see section *Prospective Modeling* and section S1-3 in supporting information S1 on the Web). If a building was demolished at a time step t, its entire inventory was treated as a waste material flow. New constructions were considered as a material input flow. Refurbishments corresponded to the difference in inventory before and after the refurbishment.

Scenario Definitions

In order to analyze the dynamics of future material flows and the resulting environmental impacts, we defined six prospective

Table 1 Scenario overview

Scenario	*Renewal*	*Material*	*Envelope*	*Description*
1 Base	0.6% p.a. refurbishment 0.15% p.a. demolition	58% concrete 37% brick 5% wood	90% standard 5% low energy 5% passive	A conservative base scenario in which no drastic changes in technology or construction were expected. The scenario describes a situation in which per-capita floor area remain constant at the level of 2015 and no additional economic or political incentives for building owners are introduced.
2 Floor area	*Base* +20% larger new constructions	*Base*	*Base*	The scenario was identical to scenario *Base*, but assumed that as of 2015 new constructions are built with 20% larger floor space per person (i.e., 59 and 62 m^2/capita for multifamily and single-family homes, respectively, instead of 49 and 52 m^2/capita in the *Base* scenario). This scenario was intended to illustrate the role of demand increase and is realistic if the current trend for smaller households and larger apartments continues.
3 Turnover	1.2% p.a. refurbishment 0.3% p.a. demolition	*Base*	*Base*	The scenario assumed an increase in building stock renewal. That means rates of demolition and refurbishment of the building envelope were doubled (see supporting information S2 on the Web). This scenario may occur when policy makers give building owners additional incentives to replace building components and invest in (energy efficient) refurbishments. It could also be triggered by a technology leap, where building technologies or construction work become less expensive and quickly penetrate markets.
4 Wood	*Base*	55% concrete 35% brick 10% wood	*Base*	In this scenario, the probability for a wood-based new construction or refurbishment was twice as high as in the *Base* scenario. Such a scenario could occur if future regulations are extended to environmental impacts of construction material, as it is already the case today for some voluntary building certification labels, or if the wooden construction style gains more popularity.
5 Insulation	*Base*	*Base*	50% standard 25% low energy 25% passive	The scenario assumed a higher share in energy-efficient refurbishments (and new constructions), resulting in much better thermal insulation of building envelopes. This scenario describes a situation where either legislation increases the requirements for thermal building envelopes or building owners adopt more energy-efficiency labels, or energy prices increase.
6 Combined	*3 Turnover*	*4 Wood*	*5 Insulation*	The scenario used the increased adoption rates of scenarios 3 to 5 (i.e., not 2). Such a scenario is realistic if legislative bodies undertake coordinated efforts and building owners quickly adopt changes in established construction customs and regulate per-capita floor area.

Note: Columns "Material" and "Envelope" refer to the number of new constructions. See section S1-2.4 in supporting information S1 on the Web for envelope scenarios. The renewal rates are calculated based on average ex-post model results, that is, the actual input is determined by means of the probability density functions given in supporting information S2 on the Web.
p.a. = per annum; m^2/capita = square meters per capita.

scenarios, each highlighting a particular model parameter. Scenarios consisted of different probability sets (see section S1-4 in supporting information S1 on the Web). Table 1 provides the reasoning of each scenario along with a summary of their respective probability sets.

Prospective Modeling

The method, described in section *Reconciling Data Gaps and Probabilistic Modeling*, was also used to determine future decisions, such as the year of refurbishment or demolition. Probability functions were based on values from literature (Wüest

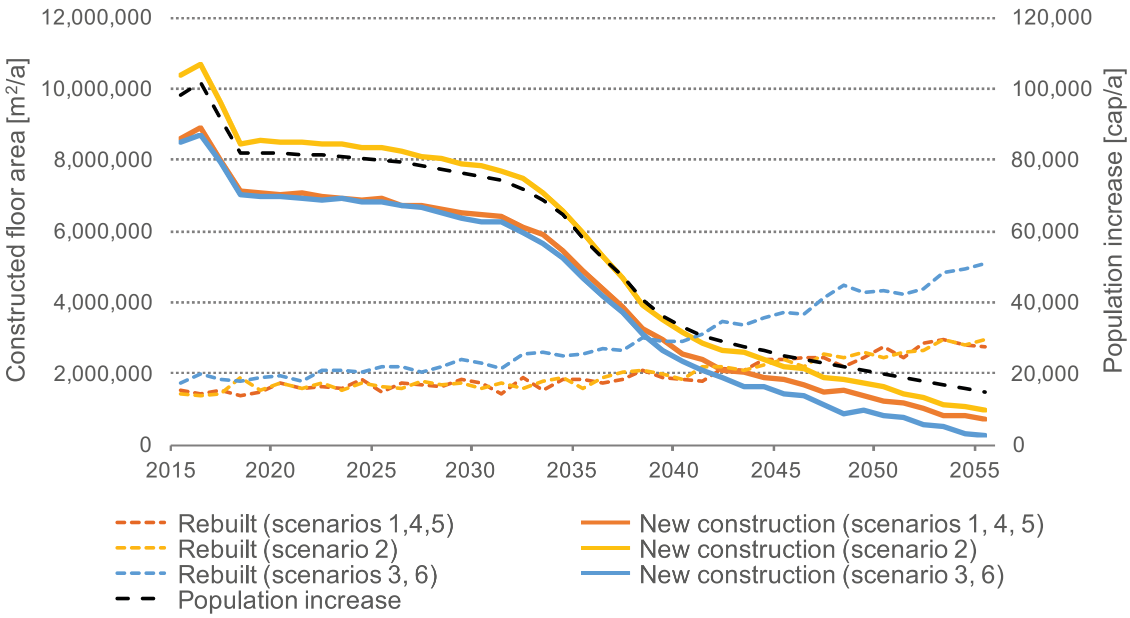

Figure 2 Annual Swiss population growth (dashed black line, right-hand y-axis) and constructed floor area (left-hand y-axis) from 2015 to 2055 for all scenarios. "New construction" denotes the floor area that is newly built every year. "Rebuilt area" denotes floor area that was reconstructed after a demolition. The peaks in 2015 and 2016 are due to incomplete data in the RDB and a difference of population accounting between the federal statistics and their forecast. cap/a = capita per annum; m^2/a = square meters per annum.

& Partner 2008; Kornmann and Queisser 2012; Guerra and Kast 2015; A. Müller 2015; Wiedenhofer et al. 2015), as well as statistical data from the city of Zurich (City of Zurich 2016). Please refer to *Reconciling Data Gaps and Probabilistic Modeling* and section S1-3 and section S1-4 in supporting information S1 on the Web for details on the procedure and supporting information S2 on the Web for the probability data.

Sampling Building Service Life and Refurbishment

Building service life is often described by survival rates, because the probability of a building demolition increases with its age (Brattebø et al. 2009; Guerra and Kast 2015).

$$y_d = X_d \qquad X_d \sim \mathcal{W}(x, k_{cp,bt,et,s}, \lambda_{cp,bt,et,s}) \tag{2}$$

We used the Weibull probability distribution function $\mathcal{W}$ to determine the demolition year y_d, as it typically produces good results for lifetime modeling of buildings (Miatto et al. 2017; Kohler and Yang 2007; Sandberg et al. 2014a, 2014b; E. Müller et al. 2014; Nägeli et al. 2015). Thus, the random parameter X_d was determined by the location k and shape λ parameters of $\mathcal{W}$. As the cumulative probability of building demolition increases with time, surviving buildings have a different probability of demolition as they had at the time of their construction. That means their probability function is truncated from below, because only the remaining buildings at the time of sampling still exist. Therefore, when sampling the year of demolition for existing buildings, we used a conditional Weibull probability function $\mathcal{W}_c$ instead of $\mathcal{W}$ in equation (2) to determine the random variable X_d.

$$\mathcal{W}_c(x, k, \lambda) = \frac{\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}}{e^{-((t_s - y_c)/\lambda)^k}} \tag{3}$$

Equation (3) describes the conditional probability density function $\mathcal{W}_c$, which accounts for the building age, that is, time step t_s minus year of construction y_c. Please refer to section S1-4 in supporting information S1 on the Web for more information, including an illustration of the conditional function in figure S1-7 in supporting information S1 on the Web.

The year of refurbishment y_{ref} was also determined by means of the $\mathcal{W}$ distribution function. Furthermore, the model selected one of six available refurbishment variants, as in Ostermeyer and colleagues (2017), and reflect material- and energy-efficiency variants (see S1-1.3 in supporting information S1 on the Web).

Floor Area Demand until 2055

Similar to D. B. Müller (2006), the model determined annual demand for new future floor area as a function of population size, which was based on the forecast by the Swiss Federal Office for Statistics (reference scenario A-00-2015). The forecast anticipates a net population growth of 26% from 2015 to 2055, with the strongest growth occurring over the next two decades (figure 2) (SFSO 2015). Demolished floor space and new floor space, necessary to meet population growth, were generated in two ways: First, demolished buildings were replaced with larger buildings (i.e., +10% floor area for single-family homes and one additional story for multifamily buildings). Other properties (occupation, shape, etc.) were maintained. Second, new buildings were "constructed" on new sites. Therefore, the number of buildings demolished each year also influenced the construction activity. Refer to figure 2 and section S1-3.11 in supporting information S1 on the Web for more details.

Life Cycle Assessment

Material flows were linked with activities from the life cycle inventory (LCI) database ecoinvent (version 3.2, allocation cutoff; Wernet et al. [2016]). For material inputs, we used European or Swiss LCI data sets for primary material. Disposal processes were typically treatment processes *for final disposal* (see supporting information S2 on the Web for a list of all ecoinvent processes). The LCI data sets remained constant over time, that is, technological innovation was not considered in our study. For the impact assessment, we applied complementary impact assessment methods. First, global warming potential from Intergovernmental Panel on Climate Change (IPCC) 2013 was used to translate greenhouse gases (GHGs) into CO_2-equivalents (CO_2-eq.), describing their climate forcing potential for a time horizon of 100 years (Stocker et al. 2013). Second, cumulative exergy demand (CExD) depicts total exergy removal from nature to provide a product, summing up the exergy of all resources required, including energy carriers as well as nonenergetic materials (Bösch et al. 2007). Its unit is megajoule-equivalent. We selected this indicator over the method of cumulated *energy* demand (often referred to as embodied energy), because it better accounts for nonenergetic resouce use. Thirdly, ReCiPe is a fully aggregating impact assessment method with 18 midpoint indicators (e.g., for eutrophication, particulate matter formation, etc.) and three endpoint indicators (Goedkoop et al. 2009). Finally, the ecological scarcity method is another fully aggregating method with a Swiss-centric "distance to target approach" (Frischknecht and Büsser-Knöpfel 2013), weighing environmental impacts according to environmental policy targets. ReCiPe and UBP are given in points.

Results

Building Stock Development

Figure 2 illustrates population growth and construction activity over time. The total annually constructed floor area is about 9 million square meters (m^2) in 2015, which corresponds to 1.0% of the total existing floor area of 854 million m^2 (see also section S1-2.4.1 in supporting information S1 on the Web). These figures are in line with recent statistics. Approximately 80% of new floor space is due to new construction and 20% due to demolition and reconstruction. According to the model, this trend is relatively stable until 2032 in all scenarios. At this point, population growth in Switzerland is expected to decrease sharply. Therefore, demand for floor space also decreases. From 2040 on, the amount of demolished and rebuilt floor area is close to the floor area from new constructions and will eventually surpass it in all scenarios.

The amount of demolished/replaced floor space constantly increases over time. The model anticipates a strong increase in demolitions shortly after the simulation period (>2055). This is because construction activity strongly increased around 1960 in Switzerland and the median service life of that cohort is assumed to be 136 years (average 135 years) according to A. Müller (2015). This effect becomes visible in scenarios 3 and 6 (blue dotted line), as it is shifted toward the left, because demolitions occur approximately 20 years earlier. In that case, the beginning of a pronounced increase in demolition activity can be observed from 2035 on. This finding should be kept in mind when discussing measures for increasing renewal rates within the building stock. Moreover, the scenarios also affect refurbishment rate and refurbishment variant (section S1-5.1 in supporting information S1 on the Web).

Changes in Material Flows

The typology that is used to determine building inventories contains approximately 160 different materials. These are aggregated to the material categories brick, combustibles, concrete, metal, mineral, glass, insulation, and wood (see supporting information S2 on the Web). The material flows from refurbishments, new constructions, and demolition change the material stocks in each time step.

Material Input

Following the pattern in figure 2 and as seen in figure S1-9 in supporting information S1 on the Web, new constructions initially dominate the material flows. With 13.8 million tonnes per annum (Mt/a), they are responsible for 91% of the material input, while refurbishment input amounts to another for 1.4 Mt/a (9%). Material outflow from refurbishments and building demolition are of similar magnitude with 1.2 Mt/a (43% of total outflow) and 1.6 Mt/a (57%). Depending on the scenario, this relationship will change until 2055. In the *Base* scenario, material input due to new constructions will decrease to 4.3 Mt/a (53%) and therefore be of almost equal importance as material input from refurbishments (3.8 Mt/a; 47%). That means total inflows have a similar magnitude as total outflows, with 3.6 Mt/a waste from refurbishments (57% of all outflows) and 2.7 Mt/a demolition waste (43% of total outflow). In scenarios with high turnover (3, 6), total material input and output flows are 38%, respectively 42% higher than in the *Base* scenario.

Figure 3 gives an overview of the material flows by category. The initial material input flow is 15.3 Mt/a and more than half are concrete-based materials, followed by minerals (e.g., from screed, gypsum boards, tiles, etc.). In Switzerland, brick construction is common, thus these constitute the third biggest fraction. Insulation materials account for 41% of *volume*-specific material input, but only 3% (0.5 Mt/a) of mass. Wood material is not only used for wooden buildings, but also as structural material and for coverage in conventional buildings and refurbishments. Its material inflow is 0.4 Mt/a.

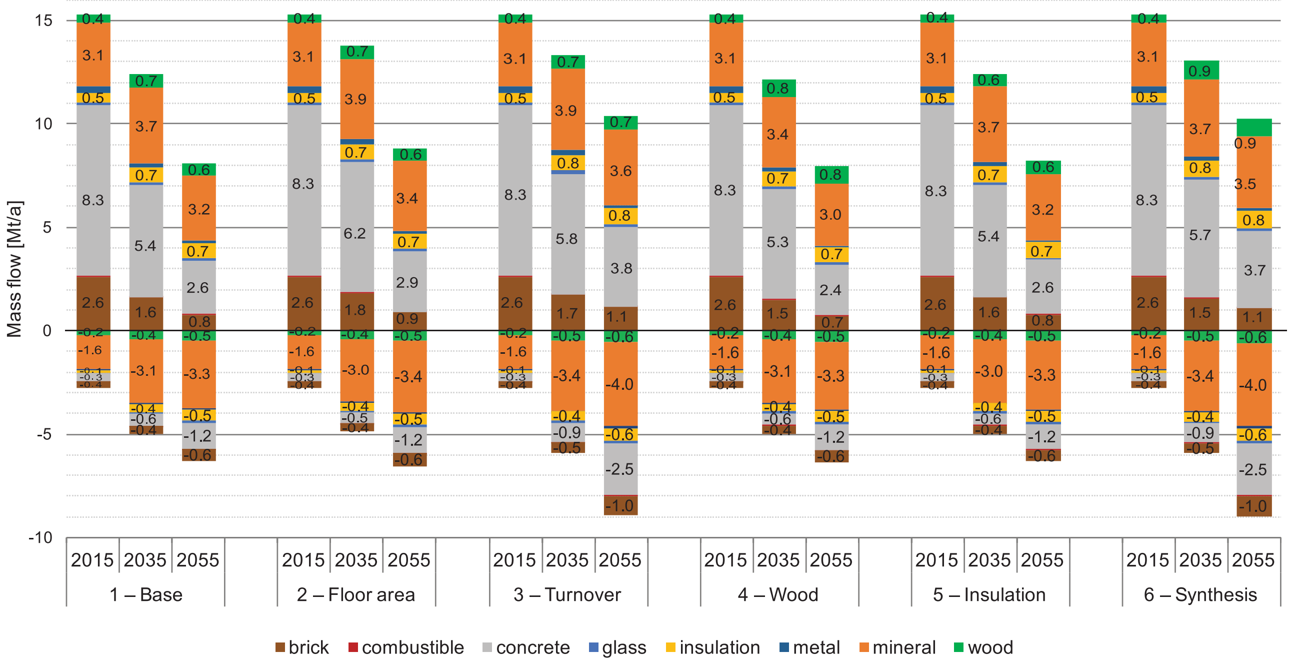

Figure 3 Material input and output for residential buildings for the years 2015, 2035, and 2055 and all scenarios. Negative values are waste flows. Numerical labels for glass and metal are omitted. 2015 values are identical for all scenarios. Mt/a = million tonnes per annum.

Due to the declining number of new constructions, total material input decreases by 47% until 2055. In the scenarios with higher turnover (3, 6), the reduction is less pronounced with 32%. Comparing the material fractions across the scenarios, their relative importance changes only slightly.

Overall population growth is the main driver and it is identical for all scenarios. Other effects, such as per-capita floor area demand or construction material, play a subordinate role. In the *Wood* scenario, around 0.5 Mt/a of the mineral and concrete material fractions are substituted with 0.2 Mt/a of wood material. The mismatch in total quantity is due to the lower material density of wood, compared to minerals and concrete, and because wood elements are typically carried out as post-beam constructions. That means the insulation layer is placed between wood beams, making them more material efficient, that is, less material for the same function (insulated exterior wall) is required. In scenario 5, the increase in insulation material input is 5% and practically not visible in figure 3. This is due to an already relatively high insulation standard in the *Base* scenario and the fact that the elements that are insulated (i.e., exterior envelope) represent only a fraction of a building. However, in the combined scenario 6, the wood and insulation material flows increase more noticeably, because turnover is increased.

Material Output

Compared to 2015, total material waste flow is more than double in 2055 (*Base* scenario). In 2055, the waste material flow amounts to almost 80% of the material input flow. This increase is due to the higher total number of existing buildings, that require regular maintenance, and an increase in demolitions. Mineral material is the most important waste fraction across the years and all scenarios. Refurbishment of the building's interior elements is a primary cause of mineral waste. Since the existing building stock consists mostly of brick buildings, the output of this material category is second highest with 0.4 Mt/a in 2015. Concrete (0.3 Mt/a) and wood (0.2 Mt/a) represent similar waste flows. The quantity of all waste streams increase, but the metal, insulation, and concrete fractions especially until 2055. Since new constructions are 20% larger in scenario *2*, material output increases from around 2050 on and is 4% higher in 2055, compared to the *Base* scenario. The higher turnover in scenarios *3* and *6* leads to an increase of 42% in waste flow. Scenarios *4* and *5* are practically identical to the *Base* scenario, illustrating the high residence time of construction material in the building stock.

Changes in Material Stock

The difference in material flows leads to a change in material composition of the building stock over time, as seen in Figure 4. Overall, a net material stock increase of approximately 25% to the year 2055 can be observed, except for scenario *2* where increase is 31%. This is because net material input is mostly driven by population increase and per-capita floor area demand. Therefore, in scenario *2*, approximately 5% more material is accumulated by 2055, compared to the *Base* scenarios.

However, material composition develops differently across the scenarios. For scenarios *1* to *3*, the material fractions are relatively similar and rather constant over time. The concrete

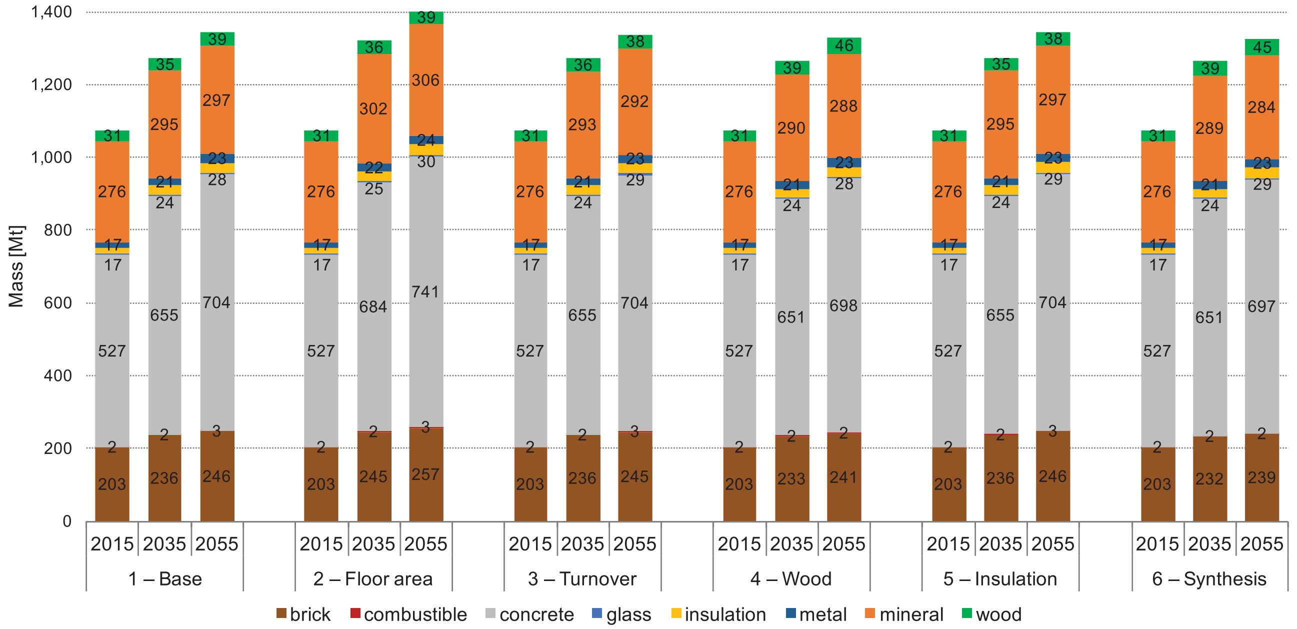

Figure 4 Material stock of residential buildings for the years 2015, 2035, and 2055 and all scenarios. Numerical labels for glass and metal are omitted. Mt = million tonnes.

fraction increases slightly and replaces mineral and brick materials. This development is due to a shift from brick to more concrete-based construction (Ostermeyer et al. 2017). In the *Wood* scenario, the wood fraction increases slightly from 2.9% in 2015 to 3.4% in 2055, substituting brick and concrete. In the *Insulation* scenario, the insulation material fraction increases from 1.5% to 2.2%. Annual material turnover is low, compared to the total material stock (i.e., 13 Mt/a net input vs. 1,075 Mt stock in 2015). That means the material stock is replaced by approximately 1% each year.

Environmental Impacts of Material Use

Annual Environmental Impacts

Current annual emissions of 4.5 Mt/a GHG emissions increase to 5.1 Mt/a in 2035 and then drop to 4.3 Mt/a in 2055 (see S1-5.4.1 in supporting information S1 on the Web). In 2015, most of the emissions are due to the construction of new buildings (75%) and materials for refurbishments (20%). Most of the GHG emissions are caused by the input of concrete (31%), insulation material (23%), minerals (18%), brick (12%), and wood (6%). Material end-of-life is dominated by the disposal of insulation material (4%) and wood (1%). Around 2040, emissions due to new construction material decline sharply, while the refurbishment material input reaches a plateau and becomes the most important contributor to total GHG at 55%. This development comes with two important implications: On the one hand, brick- and concrete-related emissions strongly decrease to 5% and 13% of total emissions, respectively. On the other hand, more insulation material is required to maintain the building envelopes, making it the most important fraction. Production and disposal of insulation material cause 31% and 11% of total emissions, respectively. The other material fractions remain mostly constant, resulting in relative changes of the results (figure S1-10 in supporting information S1 on the Web). In 2055, refurbishments continue to dominate GHG with 58%. Although total wood-related emissions grows only moderately from 2015 to 2055, wood's relative importance increases and is at 9% of total GHG, almost equal to concrete's emissions of 10%. These relationships are similar across all scenarios (S1-5.4 in supporting information S1 on the Web).

The results for the impact methods of ReCiPe, CExD, and ecological scarcity exhibit the same trend, except that the relevance of material disposal decreases (S1-5.4 in supporting information S1 on the Web). For CExD, disposal has practically no impact and refurbishment tends to have a slightly higher relative impact than new material input.

Cumulated Environmental Impacts

The cumulated climate-change impact over the years 2015–2055 is illustrated in figure 5. Total cumulated emissions in 2055 are 8% higher for scenario *2* when compared to scenario *1*. The scenarios with high turnover (*3*, *6*) show a 9% increase and the *Wood* scenario leads to a 1% reduction. The *Insulation* scenario causes 2% higher GHG emissions.

Mapping Results over Space and Time

The previous results were total results for Switzerland and discrete time steps. However, the model's design allows for far more granular assessments. Since all data are present in the form of constructional elements in a geo-referenced relational database, it is possible to zoom or aggregate to any point in space and time (i.e., year). For instance, figure 6 illustrates a

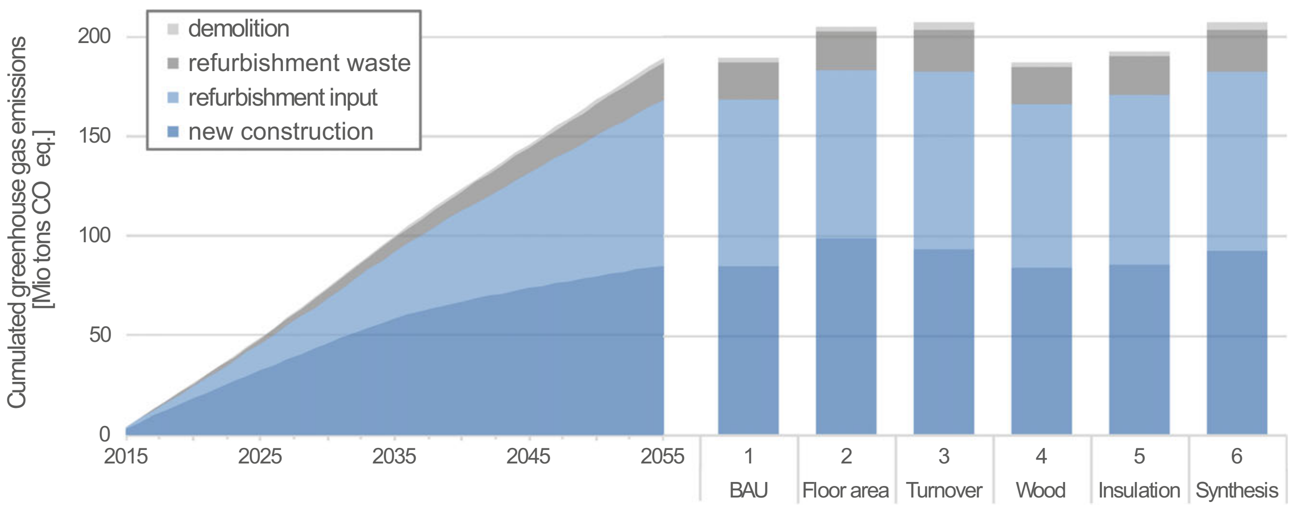

Figure 5 Cumulated greenhouse gas emissions in million tonnes from 2015 to 2055 for production and disposal of construction material. Left-hand side shows the temporal accumulation for scenario 1, and the right-hand side shows the cumulated emissions in 2055 across the scenarios. BAU = business as usual; CO_2-eq. = carbon dioxide equivalents.

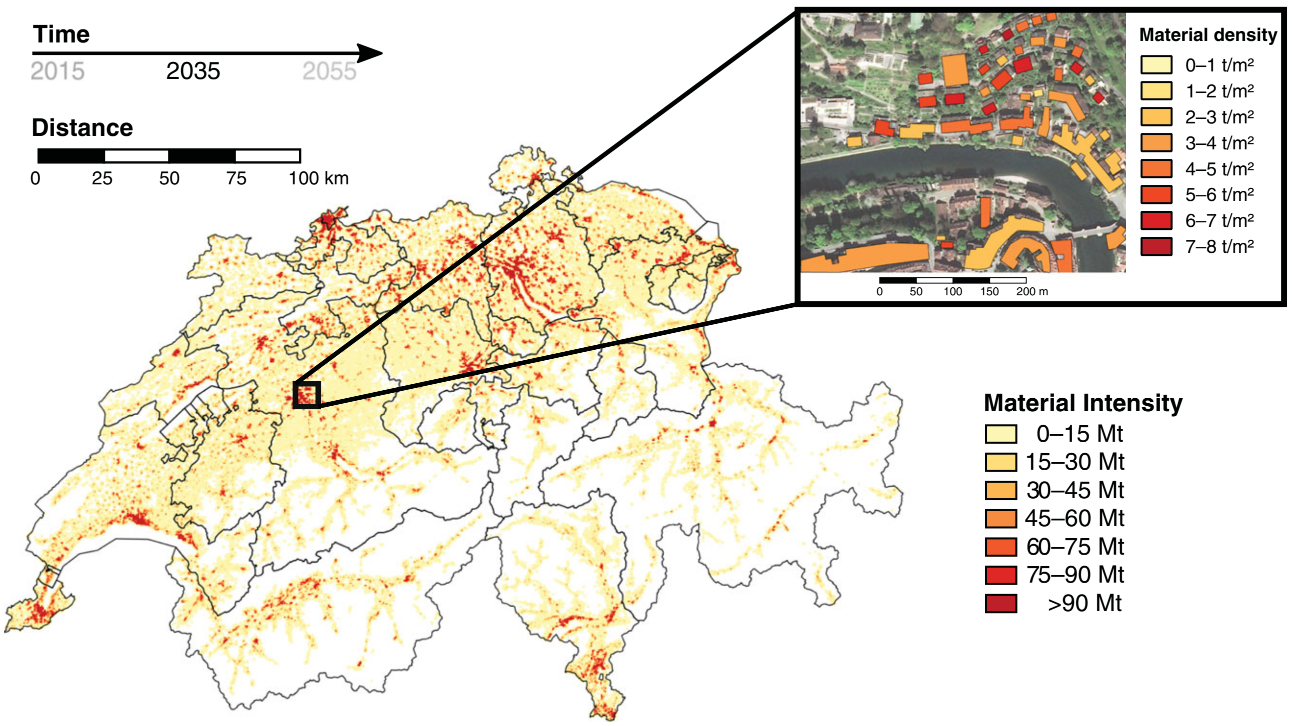

Figure 6 Mineral material stock intensity map for Switzerland and the city of Bern, residential buildings in 2035, scenario 1. Only buildings that are present in the SB3D database are displayed in the city map. Satellite image: Microsoft Bing. km = kilometers; m = meters; Mt = million tonnes; t/m^2 = tonnes per square meter.

material intensity map for Switzerland in 2025. It is possible to rescale the map for any given area or investigate particular elements, materials, impacts, scenario, and so forth. However, due to the stochastic approach, a minimum sample size must be respected. The results are only representative for groups with more than ca. 400 buildings. By comparing different time steps, it is also possible to visualize changes in material stock over time.

Discussion of Method and Model

The model yields similar results compared to the literature (see S1-5.3 in supporting information S1 on the Web for details). The demolition rate (i.e., percentage of buildings demolished each year), compared to the total stock, is similar to European or Swiss figures of approximately 0.15% (Wiedenhofer et al. 2015; Nemry et al. 2008; Thomsen and van derFlier 2011; Wüest & Partner 2008; Guerra and Kast 2015), and the number of new constructions resembles the one for construction permits in 2012 (Neubauer-Letsch et al. 2015). Material waste flow is similar to the results of Guerra and Kast (2015), but shows a more pronounced increase in the future. Total material mass in 2015 is approximately 19% higher when compared to Guerra and Kast (2015) and some of the individual material fractions differ substantially, which may be due to different definitions of material fractions (supporting information S2 on the Web).

Sources of Data Uncertainties

In Heeren and colleagues (2015), we identified material choice, building lifetime, and material service life as the most influential material-related parameters for environmental impact. The model, presented here, accounts for these parameters by means of probabilistic functions, based on empirical data. As mentioned in section *Mapping Results over Space and Time*, there is a risk of data uncertainty due to low sample size. A similar issue occurs in figure 2, where the "rebuilt" floor area fluctuates slightly over time, because the number of demolished buildings is low and their floor area varies. This can be observed when comparing scenarios *1* and *2* (orange and yellow dashed lines), where both use identical input parameters but produce slightly different results. In future work, the resulting uncertainty should be quantified.

We were able to successfully merge two geo-spatial databases and therefore improve data availability, compared to previous models. Furthermore, the use of bottom-up GIS and measured height data reduces data uncertainty, because the actual building geometries can be used, instead of archetypical ones as it is common for the archetype-based bottom-up modeling approach. However, the low accuracy of the databases limited the usefulness of the merge (S1-2 in supporting information S1 on the Web). The Swiss Office of Topography is currently working on a new version of the SB3D database, which will feature an improved height model in the future.

In general, demolition rate is a parameter that is not very well understood today and it would also be plausible to assume shorter lifetimes for certain construction periods. Our approach does not use constant renewal rates, but individual input probability density functions for building life and refurbishment (see section *Prospective Modeling*), which is more accurate than using a constant value of 0.15%. As discussed in Aksözen and colleagues (2017b), the actual rates, thus also material flows, depend on the building age composition and the individual life expectancy of buildings, which this model accounts for. Scenario *3* illustrates the implication of a faster turnover. It leads to an important increase of ca. 40% and 9% of material flow and GHG emissions, respectively. Recent publications, such as Sartori and colleagues (2016) and Aksözen and colleagues (2017a, 2017b), offer new insights on the dynamics of building stocks and the demolition rates of different time cohorts. Based on these new results, the model should be further validated in the future.

The typology, used to determine building inventory (Ostermeyer et al. 2017), does not account for all materials of typical buildings. In the future, static elements and installations should be added. Also, we did not consider new solutions aiming at material efficiency, such as digital fabrication or prefabrication. These could have an important potential in the future.

The model is designed for regionalized analysis of construction activity. However, we used mostly national data, although in Switzerland important differences in regional construction styles and economic specifics exist. Thus, the model's predictive power could be further increased by using more regionalized data, such as a local building typology, population forecast, etc.

The main driver for the model is population size and growth. The reference scenario of the Swiss Federal Office for Statistics causes a drastic shift from new construction toward refurbishment-related material flows. In follow-up work also, other population forecast scenarios should be included.

Applicability of the Model

Compared to previous studies, such as Guerra and Kast (2015), we present a model that calculates Swiss material stocks and flows for all residential buildings and has therefore a higher granularity. Decisions, such as time and type of refurbishment, are therefore made bottom-up. Hence, it is possible to model conditional scenarios that take regional- or building-specific properties into account (e.g., local resource availability, construction style, neighboring buildings, monument protection, refurbishment history, and building stock demographics). Thus, the model bridges the gap between top-down scenario analysis and building stock characteristics.

The use of a geo-spatial object-relational database gives a high degree of flexibility and allows for temporal and regional disaggregation at any given resolution down to individual years and buildings and for recombination of data with other data sets (e.g., inventory of protected buildings). This allows for policy assessment and the development of tailored strategies, such as (regional) resource planning, quantification of secondary material potentials, optimization of transport routes, etc. For instance, the geo-spatial results could be used by construction material producers, recyclers, and waste management facilities for capacity planning or determining the optimal location.

Critical Appraisal of the Method

Our analysis has also a number of limitations. In particular, the following aspects should be kept in mind when evaluating the results: (1) Prospective scenarios assumptions entail large uncertainties; (2) only residential buildings are included in the analysis; and (3) the building typology is incomplete and does not cover whole building inventories (see section *Processing Geo-Spatial Data*). According to a study by Wyss and colleagues (2014), static infrastructure (such as foundations and columns) are responsible for around 5% to 12% of total GHG emissions. The study also shows that heating, ventilation, cooling, and air-conditioning systems may cause 20% to 30%. Our study focuses on construction materials, but for a more holistic picture, these components should also be included in future work. In order to capture the related material flows, it would be necessary to enhance the building typology and develop a parametrized model for such elements. Furthermore, it should be investigated in future work how much of a building's foundations will be left in the ground in the case of a demolition.

Our model is able to illustrate the consequences of the building stock's transition from a growth state to a maintenance state. Under these circumstances and given the age structure of Swiss buildings, environmental impacts from refurbishments will become more important. This is an aspect that most "classical" building stock models were not able to account for in the past.

The model uses static life cycle background inventories, although technologies for production and disposal of materials are likely to change over time, for instance due to upscaling and learning (Caduff et al. 2012, 2014). It would be an interesting follow-up study to apply dynamic LCA approaches, similar to Collinge and colleagues (2012), Pinsonnault and colleagues (2014), and Beloin-Saint-Pierre and colleagues (2016), using inventories for future material production and disposal and investigate the time dependency of GHG emissions (Cherubini et al. 2014).

As seen in the section *Changes in Material Flows*, the time frame of the analysis is rather short. Building lifetimes mostly exceed the chosen simulation period of 40 years. However, longer simulation periods also involve more uncertainty.

In this study, we focused on residential buildings. In the future, we intend to also include other building types, such as office and industrial buildings. Although the model can be directly applied to such use cases, data availability is limited. We assume that our results cannot be directly transferred to office buildings, since renewal cycles are typically shorter and different construction typologies apply. Another interesting enhancement would be to include road infrastructure into the model. These material stocks can become as large as those from residential buildings (Wiedenhofer et al. 2015), and road infrastructure is often the most important sink for construction and demolition wastes.

Discussion of Model Results

Changing Material Demand and Its Implications

We used the reference scenario of the Swiss Federal Office of Statistics for population development. If such a scenario materializes, the construction sector will undergo important changes in the next 30 to 40 years (see *Building Stock Development*). The next 20 years are characterized by continued demand in new floor space. Around 2035, depending on the assumptions for building service life, there will be an intensive renewal cycle. At the same time, the construction activity will decline, due to considerably decreased population growth. If we assume the current demolition rate, this will lead to a situation where the amount of demolished floor area exceeds the actual demand for new area. In other words, floor area demand could be covered by replacement of demolished buildings. Higher density of the replacement buildings will further amplify this effect. That situation represents an important opportunity to reduce urban sprawl and land use. Policy should consider seizing that situation by means of regulations that aim at urban densification and penalize land-use transformation, as this is a particular issue in Switzerland.

Another structural change is that, from 2035 on, the number of new constructions reduces considerably and the next renewal cycle will take some time to occur. After 2035, policies for new constructions (e.g., on material or energy efficiency) will become far less effective. Such "lock-in" situations should be avoided (Lucon et al. 2014). That means a building that is refurbished below the technical feasible energy standard is a lost opportunity and will not be improved for another cycle. The upcoming renewal cycle is an important opportunity to replace the demolished buildings with more energy-efficient ones or do an efficient energy retrofit. The latter is particularly important, because in 2055, 70% of the buildings that were built before 2016 will still be standing (*Base* scenario), and these buildings will typically still be responsible for most environmental impacts related to energy demand (Heeren et al. 2013). Legislation should therefore give building owners incentives to choose the most energy efficient solution for a refurbishment or a replacement building.

Environmental Impact Due to Material Flows

In Wallbaum and colleagues (2009) and Heeren and colleagues (2013), we quantified annual GHG emission due to energy consumption of Swiss residential buildings as being 18.9 Mt/a CO_2-eq. and calculated a possible reduction to 6.7 Mt/a CO_2-eq. by 2050. Such a scenario, however, requires both substantial reductions in energy demand and a radical change in energy supply. In the present study, annual emissions due to material turnover is around 4.5 Mt/a CO_2-eq. and none of the scenarios show significant reductions by 2050. Hence, when considering the entire building life cycle, reducing use-phase emissions caused by building energy consumption is, at the moment, probably the more powerful leverage. Moreover, that means the contribution of construction material to total life cycle emissions of residential buildings will increase from 19% in 2015 to 39% in 2050. In a future where all buildings are very energy efficient, this situation could reverse and material impacts outweigh energy-related ones (Kristjansdottir et al. 2017). The results of the six scenarios differ only by relatively small margins, which is due to the long investment cycles and the resulting slow turnover within the building stock. Therefore, construction material policies will have a significant delay before showing effects.

Scenario 2 – *Floor area* highlights the relevance of per capita floor area demand. Legislation should offer incentives to halt its ongoing increase. An increased turnover, as seen in scenario 3, is necessary to achieve a better energetic performance of the building stock (Heeren et al. 2013), but temporarily results in higher material impacts. An increased refurbishment rate is only useful if the refurbishments yield net environmental savings (i.e., energetic saving minus material impact must be greater than zero). Therefore, refurbishments should always be analyzed for their life cycle impacts.

The *Wood* scenario (4) illustrates the importance of the choice in construction material and material efficiency, despite its small environmental benefits. In future work, the maximum amount of locally available resources, should be explored (Ioannidou et al. 2015). Our model allows for mapping material flows, thus assists in the planning of regional transport and recycling strategies.

A particular aspect of wood is its capacity to sequester carbon from the atmosphere. One cubic meter of softwood contains around 250 kilograms (kg) of carbon, which corresponds to 1 tonne of CO_2 fixation. Compared to the *Base* scenario, in scenarios 4 and 6 about 7 Mt more wood-based materials are stored in the building stock by 2055, which corresponds to an avoided emission of 12 Mt CO_2, as the forest continually regrows and sequesters new atmospheric carbon. This temporary storage persists during the service life of the element. Net benefits of wood carbon storage on global warming are subject to an ongoing scientific debate (Cherubini et al. 2012, 2016; Gustavsson et al. 2017). Apart from the biogenic carbon storage, other building materials represent considerable carbon stocks, such as bitumen and plastics (Lauk et al. 2012) or concrete, due to calcination and carbonation (Xi et al. 2016).

The additional insulation material used in scenario 5 causes relatively few additional environmental impacts. Therefore, it is likely that such a scenario will yield a net benefit, if energy demand of buildings is also accounted for. Scenario 6 causes similar impacts as the *Turnover* scenario, implying that wood construction has the potential to compensate for the additional emissions that are due to the additional insulation material.

Potentials to Close the Material Cycles

As illustrated in section *Changes in Material Flows*, the total material output in 2055 is almost 90% of the material input, especially in scenarios with increased turnover. Such a situation represents an ideal basis to close material cycles in the future. So far, we have used life cycle inventories for primary construction materials (except for the material flows inherent in ecoinvent). In reality, at least some of the material will be treated and reused in similar applications or for other purposes.

In order to estimate the potential of circular material flows, we carried out a sensitivity calculation, where we assume that the waste material flow substitutes a primary product. This way, less primary products need to be produced, which means environmental impacts are avoided. This avoided impact is referred to as *credit*. Since brick and concrete waste (1.8 Mt/a) is less than concrete demand (2.6 Mt/a) in the scenario *Base* for 2055, we assume that these materials can be crushed and, to a certain extent, substitute primary aggregates in different applications (Hoffmann et al. 2012). Thus, they substitute 1.8 Mt/a of primary gravel and receive respective credits. This calculation quantifies the maximum potential, neglecting the losses occurring during the recycling process. Nevertheless, the benefit is relatively small, reducing the total GHG emissions in 2055 by 0.5%. Using the same reasoning, we give waste wood material credits for substituting primary sawnwood, which yields in a reduction of total GHG emission by 0.6%. However, recycled wood could still be combusted. Therefore, we also looked at a substitution of thermal and electrical energy by wood material as municipal solid waste incineration plants in Switzerland are typically combined heat and power plants with average conversion efficiencies of 25% and 13%, respectively (Heeren et al. 2015). This scenario reduces impacts by 3.4%. Swiss manufacturers of rock wool and polystyrene currently investigate options for material recycling of thermal insulation (Jakob et al. 2016). Although such technologies are not yet ready for mass deployment, we calculated their maximum potential environmental benefit by assuming the substitution of primary insulation material. Such a closed material loop would yield a 24.8% benefit, compared to the base disposal scenario. Results are illustrated in figure S1-17 in supporting information S1 on the Web.

These approximative calculations illustrate the importance of closing material cycles on the highest possible level or even direct material reuse. The lower the quality of the substituted product, the lower the environmental benefit will be. Therefore, it is advisable to focus material research on high-quality substitution, such as recycling of insulation material.

The aspect of secondary materials should be further investigated. For instance, Knoeri and colleagues (2013) show that the environmental benefit of recycling concrete strongly depends on the amount of additional cement and transport distance of the secondary material.

The mineral material fraction has the highest growth rates within the next years. This is due to modern construction styles using more gypsum and screed. It should be investigated if such an increase can be handled by means of current disposal technology.

Conclusions and Outlook

We illustrated the feasibility of combining the following techniques: (1) Detailed building volumes are determined from three dimensional GIS data sets. (2) Construction material flow and stock is determined and processed bottom-up on a national scale. (3) Probabilistic scenarios are used to describe building stock development over time. (4) Material flow is determined dynamically into the future. (5) Data are interlinked by means of a geo-spatial object-relational database. The combination of these techniques represents an important advancement in bottom-up building stock modeling, because it moves beyond the common archetype approach, improves data accuracy, and bridges the gap between the individual building and the building stock scale. The model offers a high degree of flexibility makes results (material flows, LCA impacts, etc.) scalable over space and time and allows for new applications.

Thermal insulation material is identified as a particularly problematic material fraction. By 2035, its material flows will increase considerably and insulation material will become the fraction with highest environmental impacts. Moreover, disposal can be problematic, as in the past it was often contaminated with flame retardants, etc. (Sprengard et al. 2013; Jakob et al. 2016). Nevertheless, insulation material is necessary for making the building stock more energy efficient. We are working on a follow-up publication which investigates this trade-off more closely by coupling the material flow model with a thermal energy demand simulation. To that end, we developed a new thermal model featuring an improved three-dimensional building database and new approaches for energy demand calculation (Buffat et al. 2017).

An important finding of the dynamic mass flow analysis is the upcoming structural change in the Swiss building stock. It will transition from a growth to a maintenance state, which means that there is an important opportunity to close material cycles, as future waste and input material flow will have comparable magnitude. This has the potential for significant reductions of environmental impact, if material substitution can be realized on a high-quality level.

Our scenarios represent realistic developments in the construction sector; however, none of them lead to meaningful reductions of environmental impacts within the coming decades. End-of-life material recycling, wood construction, and material efficiency are promising strategies, but it will take considerable time before they show effect. Compared with the reduction potential from reducing energy consumption during the buildings' use phase (Heeren et al. 2013), material flows appear as an unresolved issue. If material-related impacts are to be reduced substantially, more ambitious measures than the ones discussed currently are required. This finding applies specifically to the system dynamics of the Swiss building stock, but growing stocks, such as China and India, will also require new strategies. Their infrastructure growth is expected to cause significant carbon emissions and they cannot resort to the closing of secondary material cycles (D. B. Müller et al. 2013).

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Supporting Information

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

Supporting Information S1: This supporting information provides additional details concerning data sources, algorithms, and results.

Supporting Information S2: This supporting information provides the probability data used for sampling refurbishment and demolition year, as well as material data and impact results as used for the (LCA) calculations.