Integration of materials in life cycle assessment (LCA) of buildings: tool for future renovation scenarios

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ARTICLE INFO

Keywords:
Buildings
Life cycle assessment
Embodied impacts
Operational impacts
User interface
Scenarios

ABSTRACT

models Done

TODO
> Residential buildings have a significant impact on the global emissions.
> There are many studies evaluating operational and embodied impacts of buildings separately.
> But not many integrate them, especially while considering the impacts of the materials on both embodied and in-use impacts. (studies exist) eg. Niko
> Thus we develop a interface where this material data can be integrated with models estimating in-use demands, giving a final LCA of buildings.
> We further add scenarios to estimate the maintenance phase of the building as well for a case study data.
> Our results show clearly that our model helps estimate the in-use emissions better (more accurate).
> scenarios in this case, for new buildings, show that energy source change is effective but insulation addition is not always as effective to save building's impacts.
> Model can be used to test for other types of buildings, where the results on the same scenarios may vary.

operational GHG: negative C-storage from wood as material → mention in outlook as future research

Done, added as a point in discusisons

1. Introduction

Nearly one third of the total global final energy consumption can be attributed to the buildings and building construction sectors (IEA, 2022). Together these two sectors are responsible for a large share of globally emitted greenhouse gases (GHG). The potential for emissions reduction presents a great opportunity for both newly engineered as well as already existing building stock (Jennings, Hirst, Gambhir et al., 2011).

GHG emissions are released throughout all lifecycle stages of buildings starting from construction, and ending with final demolition. Researchers distinguish between *operational emissions* from energy demand for space heating/cooling, lighting, ventilation and the use of appliances, and *embodied emissions* arising from extraction and processing of raw materials, manufacturing and transportation of building components, buildings construction, maintenance and renovation (Ramesh, Prakash and Shukla, 2010). Past studies estimated a rather small magnitude of embodied emissions compared to operational emissions accumulated over the complete life span of buildings, with the respective shares being 10-30% and 70-90% (Ramesh et al., 2010; Adalberth, 1997; Utama and Gheewala, 2009). However, nowadays, due to better insulation, enhanced building designs, and higher environmental performance of energy sources, the operational emissions have been decreasing, while the shares of embodied greenhouse gas (GHG) emissions increased (Chástas, Theodosiou, Kontoleon and Bikas, 2018). For these reasons, there is a shift from studies with a sole focus on operational energy demand and towards more comprehensive assessments that include both operational and embodied impacts (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida and Acquaye, 2013).

Assessment of energy demand, GHG of residential buildings, and potential mitigation pathways is possible by means of building stock models (Nägeli, Camarasa, Jakob, Catenazzi and Ostermeyer, 2018). They are commonly categorized into top-down and bottom-up approaches (Swan and Ugursal, 2009; Kavgic, Mavrogianni, Mumovic, Summerfield, Stevanovic and Djurovic-Petrovic, 2010; Keirstead, Jennings and Sivakumar, 2012; Reinhart and Davila, 2016; Sun, Haghighat and Fung, 2020). The former analyze aggregate energy consumption of the entire residential sector, and use historical data to understand future trends as a function of broader technological and econometric

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factors, such as income, fuel prices, technological advancements, and others. However, top-down models do not allow detailed analysis of buildings' environmental performance. In contrast, the bottom-up methods investigate characteristics of individual buildings and quantify their energy consumption and environmental impact depending on building properties. This allows for explicit modeling of e.g. renovation scenarios.

Buffat, Froemelt, Heeren, Raubal and Hellweg (2017) introduced a bottom-up model to estimate building space heating demands based on large-scale geographic information systems (GIS), and with high temporal resolution. By employing light detection and ranging (LiDAR) data in combination with digital elevation models and building footprint data, the authors were able to derive building geometries and accurate building volumes. At the same time, digital elevation models in combination with 30-minute temporal resolution of spatial climate data, allowed to evaluate solar gains through windows and shading effects while accounting for the surrounding topology. This study showed that in computing the spatially-explicit heating demand, the most sensitive parameters are room temperature and thermal transmittance (U-values) of materials in building components such as floors and walls. Despite recognizing the importance of the U-values, they have been artificially sampled for each building from a generic probability distribution constructed according to the building type and construction period. This approach leads to low accuracy of the U-values.

A more comprehensive analysis to estimate the U-Values requires primary data on the material composition of the building components. It can be obtained from building owners, planners and architects. These datasets can be helpful in better estimations of not just the U-Values, but also the embodied emissions of buildings. One of the ways to include them lies in providing an interface to the building stock models, where model users can input additional building data to overwrite the default values. As the total emissions of a building are affected by multitude of parameters, the possible user inputs should not be restricted to material data, and should incorporate other building properties including its volume, geometry, ventilation flow rates, and others. Such interfaces exist as propriety software platforms that have limited flexibility with respect to user inputs and possible parameter modifications (for instance, most of them do not allow inputs on windows and their properties). The other type of models allowing user interfaces are called Building Information Models (BIM) (Azhar, 2011; Anand and Amor, 2017). They allow better range of inputs than the proprietary tools, and in some cases also integrated Life Cycle Assessment (LCA) to estimate building emissions (Soust-Verdaguer, Llatas and García-Martínez, 2017). However, none of the existing BIM models compare in complexity to the building stock models. Thus, there is a clear need of a tool that combines flexible user inputs with elaborate building stock models.

The aim of this study is to provide a model that pays equal attention to more accurate estimation of both embodied and operational emissions of residential buildings. To this end, (1) we conduct life cycle assessment to estimate building impacts from operational emissions, given more precise space heating demand estimates, and compute embodied emissions from the material data; (2) for better operational emissions estimates, we improve the GIS-based bottom-up energy demand model from (Buffat et al., 2017) by replacing the generic probabilistic U-values with building specific material composition data; (3) we develop our model as a tiered tool to allow for integration of additional building data and sequential user inputs; (4) we apply our model to a case study of 12 Swiss residential buildings containing detailed building data that, among other information, includes material compositions John (2012); (5) for this case study, we introduce and evaluate impacts of two renovation scenarios and their potential environmental benefits; and finally (6) we validate U-values, space heating demands and embodied GHG emissions with reported data from the case study.

The paper is laid out as follows to achieve the above aims: first, we provide the datasets used in the study (Section 2), followed by discussion of our model, which estimates the total operational and embodied emissions of the building (Section 3). Then, we introduce a case study (Section 4) to validate and showcase our results (Section 5). Finally we conclude the paper with further discussions and outlook (Section 6 - Section 7).

Outlook
disposal dat

Not clear

2. Data

In the following, we provide a description of various datasets used in this research. The overview of the datasets is listed in Table 1.

2.1. Building properties

In this work we employ a dataset that contains information about high-level building properties. The main source of this data for Switzerland is the Federal Register of Buildings and Dwellings (FRBD) that collects the ~~most important~~ basic data about individual buildings (FSO, 2022). The Register has been established in 2000 on the basis of a buildings

Done

Table 1
An overview of the datasets used in the model

Category	Dataset source	Parameters
Building properties	Federal Register of Buildings and Dwellings (FSO, 2022)	Building identifier number Added (address) ? Canton and municipality → also location ? ~~Number of floors~~ Done Number of accommodation units Type and year of construction Year of renovation Energy reference area Heating and warm water sources
	Done Cadastral survey, ? Buffat et al. (2017) Orthofoto ETC	Geocoordinates Footprint area Done Shading?
Building components Properties of.. dimensions	Digital elevation models (swisstopo, 2022) Statistical estimations (see Statistical build. data)	Building volume ~~External and inner~~ wall areas Number of floors Roof area Replaced with window config Windows dimensions
Materials of building components	Material intensities based on: - (Heeren and Fishman, 2019) - (Heeren and Hellweg, 2019) - (Gauch et al., 2016) ? not in original ? → check Not clear	Materials used in: now also Joh - façade - walls and windows - roofs and ceilings - floors Not included as we do not have this Structure? Components
	Material compositions from: - literature sources - architects and planners - building owners	
Material properties	Literature sources Done (see comprehensive list in the SI excel)	Thermal conductivities of: Added a section - walls and windows Verificatio - roofs and ceilings rate ? - floors ~~Included in properties of building components~~
Site data	Climate (MeteoSwiss, 2022)	Daily mean temperature
	Solar radiation (Müller et al., 2015)	Global irradiance Direct normal irradiance Cloud albedo
	Digital elevation models (swisstopo, 2022)	Geocoordinates Shading effects ✓
Environmental data	Life cycle inventories from ecoinvent (Wernet et al., 2016)	Energy and material inputs in product systems Done Emissions to and from the natural environment Background other than material
	Life cycle impact assessment (Stocker, 2014; Myhre et al., 2014)	Global warming potential values for greenhouse gases (100y)
	KBOB platform (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) (KBOB, 2022) IPCC?	Impacts per kilograms of various construction materials

and dwellings survey, and is maintained by the Swiss Federal Statistical Office (FSO). Nowadays it contains a wide variety of building types with an extensive coverage of residential buildings. The specific building parameters provided by the FRBD are listed in Table 1, and include physical parameters, information on building's construction and renovation, as well as energy and warm water sources. In addition to the FRBD, Buffat et al. (2017) computed better estimates for building footprint areas that include sets of polygons describing geocoordinates, shapes and dimensions of each building in Switzerland.

properties.. (includes dimensions and configurations..)

2.2. Building components ~~dimensions~~

The Swiss Federal Office of Topography (swisstopo) is a crucial source of geoinformation data in Switzerland. It is responsible for the collection, management and provision of official geodata and the provision of spatial services (swisstopo, 2022). Swisstopo has a long history of developing high-resolution digital elevation models of Swiss landscape such as (1) digital surface models (DSMs) that incorporate all items above ground, and (2) digital terrain models (DTMs) outlining the bare ground natural terrain, excluding natural and built surface objects. Following previous research in combination with the building properties dataset described above, these models were used to derive building volumes, areas of walls, number of floors, orientayion and location configuration of windows and other attributes of various building components ~~to estimate building heat demands~~ (Buffat et al., 2017; Buffat, Heeren, Froemelt and Raubal, 2019). ?

done ... not clear.. how consolidated w/ FRBD?

2.3. Materials of building components what materials? thickness? Done

The type and amounts of materials used in building components constitute life cycle inventories that are needed to estimate buildings embodied emissions. At the same time, component areas and material data allows for the computation of the heat losses from walls, roofs, ceilings, floors and other components of a building during its operational phase (see Section 3.2). This information can be provided as material composition or material intensity data. Done

definition of material

Material composition can be defined for various building components, and is expressed as thickness of each constituting material in the component's cross-section. The composition includes but is not limited to construction, cover, finish, and insulation materials. For instance, floor composition might include combination of insulated wood panel, bitumen membrane, cement cast plaster floor and concrete floor slab. Material composition data can be collected from architects, planners and building owners, as well as from literature sources. In case it is not available, we use the default material intensities of buildings instead. Done layers Done

Done or remote sensing for concrete layers

Material intensity is the total mass of a construction material present in an entire building divided by the building's volume (or sometimes its floor area). In this work, we assembled a dataset with mass-to-volume ratios of minerals, TO DO metals, timber, brick, concrete, and combustible materials for typical Swiss buildings based on a literature review (Heeren and Fishman, 2019; Heeren and Hellweg, 2019; Gauch et al., 2016). Due to the changes in material technology and policies on sustainable construction, materials used in the construction of buildings evolve significantly over time. This is reflected in the developed dataset by choosing the typical buildings and allocating their respective material intensities based on the construction periods, each spanning at least 15 years. We validated the constructed dataset with (1) an existing building model from an architecture firm, and (2) the study on waste from building materials conducted by the Federal Office of Environment (Guerra and Kast, 2015) (see SI excel). ?

2.4. Material properties

Each construction material has different physical properties that determine its contribution towards the overall emissions of a building. In our model, one such important property is thermal conductivity - the rate at which the heat is conducted through material (Bird, 2002). It is measured in watts per meter-kelvin [W/mK], ranging from 0.01 W/mK for gases and all the way up to 1000 W/mK for metals, where lower values point to better insulators. Based on various literature sources, we have collected thermal conductivity of 165 materials, including timber, concrete, insulation, and other materials of varying densities (see SI excel). Subsequently, thermal conductivities allow us to compute thermal transmittance, or U-value, that is the heat transfer coefficient describing how well a building component conducts heat (see Section 3.2).

Ventilation rates Section Done

To discuss:
~~Do we need a section here? Is it not sufficient to add it to properties of building components?~~

2.5. Site data

In addition to the building and material datasets described above, the location of buildings significantly affects their environmental performance. For instance, **climate** conditions, such as local air temperature and solar radiation, influence heat flows between building components and its surroundings. To compute time-series of heat losses, Buffat et al. (2017) used the temperature data collected by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss for the years 1994-2013 that contains daily mean temperature values on the 1.6 km in longitude and 2.3 km in latitude resolution (MeteoSwiss, 2022). To account for the effects of solar radiation, the authors employed the spatially and temporally explicit surface **solar radiation** dataset Heliosat (SARAH) provided by the Satellite Application Facility on Climate Monitoring (Müller et al., 2015). It contains solar radiation data for the entire Switzerland given on a 30 minute basis, and on a 3.8 km in longitude and 5.6 km in latitude grid. Combining these datasets with the **digital elevation models** that can account for the shading effects of neighboring structures, provides a more complete picture about the contribution of site conditions to building performance.

which datasets (not materials → specify SI)

2.6. Environmental data

Sasha?

In order to compute operational and embodied emissions of buildings, life cycle assessment environmental data is needed. In this work we used ecoinvent - a well-established **life cycle inventory** (LCI) database that contains (1) datasets on energy and material inputs in a wide variety of product systems present in global supply chains, as well as (2) natural resources taken from the natural environment and emissions released to the water, air and soil (Wernet et al., 2016). We focus on the climate change **life cycle impact assessment** method, with the global warming potential values of greenhouse gases estimated in the Technical Report by the Intergovernmental Panel on Climate Change (IPCC) (Stocker, 2014; Myhre et al., 2014). For the materials, we employ data available on the **KBOB platform** (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) (KBOB, 2022). KBOB datasets were originally based on ecoinvent. They contain impact assessment results for various construction materials, while taking into account services, transport and energy systems representative specifically for the building sector in Switzerland. For example, climate change impacts are given in kilograms of CO_2-equivalents per kilograms of materials.

changed tier to step everywhere

3. Model

step-wise

The above described data was taken from various models and literature sources. However, in order to obtain more accurate estimates of emissions for a particular building, it is preferable to replace general values with the building's specific measurements that can be provided by architects and building planners. Thus, in our model we make a provision for such model "users" to complement the existing building properties, components and material compositions with additional data. To that end, we ~~have~~ developed a ~~tiered~~ model that takes user inputs, and yields more accurate estimates of the building cumulative emissions, as shown in Figure 1. The ~~tiers~~ steps were laid out in the order of sequential user inputs, and with the objective of calculating the total emissions of a building. The final ~~tier~~ step 5 collects data on (1) operational emissions due to the space heating demand computed in tier 4, and (2) embodied emissions which need the material components and properties data gathered (from a user) in the tiers 1-3.

Added a line on tiers

The described model was developed in Python[1] to complement the model of Buffat et al. (2017), and is available as a Github repository[2]. At each tier of the model, default building characteristics are combined with available user inputs and passed as a python dictionary[3] onto the next tier. The implemented user prompts, examples of user provided inputs, and default model values are listed in the SI excel document. In the following, we first provide an overview of the tiered model, then detail the model calculation processes in Sections 3.1-3.3, and finally in Section 4 we apply the model to a case study of 12 residential buildings in Switzerland (John, 2012).

Done

step **Tier 1:** In the first step, the user inputs the unique building identifier or building geocoordinates, from which the tiered model derives the **building properties** (FSO, 2022; Buffat et al., 2017). For Swiss buildings, the identifier is "Eidgenössische Gebäudeidentifikator (EGID)", or unique federal building identifier, allocated to each building in Switzerland. Based on the user input, the model locates the building and assigns it default building properties. In cases, when the model is not able to find the exact match due to missing information, it prompts the user with further questions on other building properties, and then employs the "least distance approach" that finds closest building in the database, where "closest" refers to similarity in terms of building properties. As we use this approach for our case study, it is further explained in Section 4.1.

dimensions nice!

step **Tier 2:** Next, the user is prompted to provide the information on different **building components**, such as areas of walls, roofs and number of floors. If no data is available, the building components are derived with the digital elevation models (Buffat et al., 2017). Otherwise, the user is asked to provide information on the components and their respective **material compositions**. In case the detailed material compositions are unknown, the model assigns the default **material intensity** values for the building based on its construction year. If, on the other hand, the user can provide the material composition data, then the tiered model allocates materials and their thicknesses to the various building components.

step **~~Tier~~ 3:** When the material composition data is available, each material is linked to its respective **material properties**. Knowing the thermal conductivities and thicknesses of materials in a building component, one can

[1] https://www.python.org/
[2] https://github.com/rhythimashinde/building-model
[3] https://docs.python.org/3/tutorial/datastructures.html#dictionaries

Tiers for information level

Tier 1: no user information

Tier 2: ...

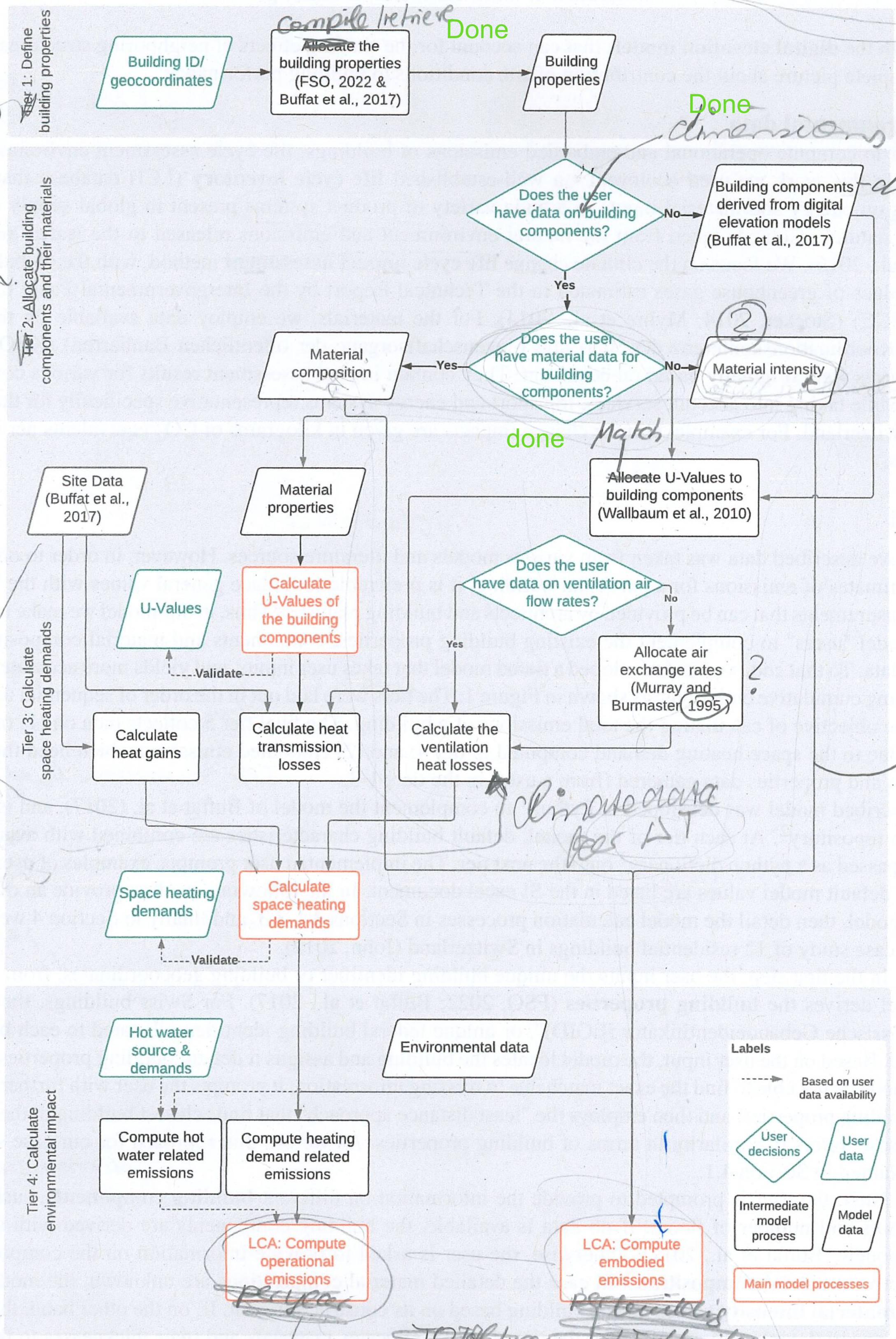

Figure 1: Methodological approach for material-data integration and validation

calculate the component's thermal transmittance, also called the U-Value (see Section 3.1). In case the users cannot provide the material compositions, the tiered model selects default U-Values for each building component based on its construction year (Wallbaum, Heeren, Jakob and Martius, 2010). Once the U-Values are allocated to the building components, the model estimates the heat transmission losses, which contribute towards the building's space heating demand (Section 3.2). In this ~~tier,~~ step we also account for the heat gains and ventilation losses based on the air exchange rates, either provided by the user or taken from (Murray and Burmaster, 1995). Notably, we make provision for the model validation if the user provides the U-Values of the building components, and the space heating demand of the building (preferably measured).

mentioned in ventilation data (from ecoinvent v3...)
that we only stick to natural ventilations

Step **~~Tier~~ 4:** Finally, the ~~tiered~~ model estimates total building GHG emissions, based on **environmental data** (Section 3.3). Operational emissions are computed ~~knowing~~ well (1) emission factors per unit of space heating demand and the space heating source (part of the building properties); (2) hot water demands and source in case this data is given by the user. Embodied GHG emissions are calculated based on the collected material information data (~~either~~ material compositions ~~of building components or material intensities~~). and component dimensions)

also with the material intensities you assume a material composition? and otherwise? yes, mentioned in MI para

3.1. Calculate U-Values

In the ~~tiers~~ steps 1-2, the user is prompted to provide the construction and insulation materials used in the walls, roofs, ceilings, windows and floors of a building. The purpose of gathering this information is to estimate how each of the building components loses heat given its exposure to the outer air or (un)heated spaces of the building, and thus contributes to the space heating demand (see Section 3.2). These heat transmission losses are denoted as Q_T and are primarily defined by the thermal transmittance, or U-Value, of the building components. For a component c, its U-Value U_c is calculated based on the properties of constituting materials:

added e.g.

its given below..

and the temperature difference inside-outside (site data)

did you model that?

$$U_c = \left(\sum_i \frac{t_i}{k_i} \right)^{-1}, \quad (1)$$

e.g. added

where t_i is the thickness (m) and k_i is thermal conductivity (W/mK) of a material i. Note that the considered U-values (W/m^2K) fall into 6 categories: (1-3) floors, roofs, and walls against outside air, (4-5) floors and walls against unheated spaces, and (6) walls against adjacent heated spaces. If there are multiple U-Values in one of the categories listed above, e.g. several walls against outside air, then we select the average U-Value for that category. If no material composition data is available for a building component, the model allocates its U-Value based on the construction period and renovation rate of the building as estimated by Wallbaum et al. (2010); Heeren, Jakob, Martius, Gross and Wallbaum (2013).

how determined?

removed

why needed?

3.2. Calculate space heating demand

The goal of ~~tier~~ step 3 is to calculate the total space heating demand in order to later estimate the final operational emissions. In our model (as in Buffat et al. (2017)), the space heating demand is defined by SIA-380/1 (2009), which is a building heat model used in Switzerland to verify that buildings meet the heating insulation obligations. This SIA model estimates the heat demand of a building using a monthly steady-state method while providing fairly accurate results across different building stocks. It defines the heat demand (MJ) of a building Q_H summed over different time periods t as follows: ?

updated

resolution? so ... updated

$$Q_H = \sum_t \sum_c Q_{T,t,c} + Q_{V,t} - Q_{G,t}, \quad (2)$$

where Q_T are the heat transmission losses, Q_V are the ventilation losses, and Q_G are the heat gains.

Heat transmission losses Q_T occur in different building components c including windows, walls, floors and roofs. For each component they are measured based on the component area A_c (m^2), its U-Value U_c, the temperature difference $\Delta_{T,c}$ (K) between warmer and colder areas, and reduction factor b_c due to reduced thermal losses from surfaces whose thermal conductivities are unknown, such as walls against unheated rooms and soil: ?

updated

$$Q_{T,t,c} = A_c \cdot U_c \cdot \Delta_{T,t,c} \cdot b_c \quad (3)$$

How determined which part of the building was heated/unheated?

not scope of the model ... newer buildings: careful, if there is mechanical ventilation, windows are typically not opened → adapt model!

Ventilation losses Q_V depend on the air exchange rates a $(1/h)$ affected by the presence of inhabitants and their behavioral changes (such as keeping windows open), where the rates are derived from a probability distribution following the approach of Murray and Burmaster (1995). Additional to the air exchange rates, the losses are modelled by taking into account the volume V (m^3) of the building, which is either given by the user or the digital elevation models (Buffat et al., 2017), and the specific heat storage capacity of air s $(MJ/m^3/K^1)$:

$$Q_{V,t} = a_t \cdot V \cdot \Delta_{T,t} \cdot s \tag{4}$$

In addition to including these various contributors, our ~~tiered~~ model prompts the user to provide the air flow rates, f (m^3/h) to estimate the air exchange rate a and replace the probabilistic values in the model whenever possible:

not sure..
heat recovery option in artificially ventilated zones?

$$a_t = \frac{f_t}{V} \tag{5}$$

Heat gains Q_G of a building include solar heat gains Q_S (MJ/m^2), cumulative heat gains from electric devices Q_E (MJ/m^2) and cumulative heat gains from the inhabitants Q_P (MJ/m^2), weighted by the degree of utilisation η_g of the cumulative heat gains:

$$Q_{G,t} = (Q_{S,t} + Q_{E,t} + Q_{P,t}) \cdot \eta_g \tag{6}$$

Here, the solar heat gains are derived from the site data that considers the solar radiation at different times of the day, sizes and orientations of windows in a building, energy conductivity of each window, and the shadowing effect of the neighboring building as estimated in the digital elevation models. The electricity heat gains are based on typical electricity heat gains per year and the energy reference area of the building (SIA-380/1, 2009). The heat gain from inhabitants is modelled from the occupancy and heat produced per inhabitant (Buffat et al., 2017). The ~~tiered~~ model allows the users to additionally update the occupancy, the energy reference area of the building and the windows size and orientations to refine the estimations of the total heat gains.

nice!

3.3. Life cycle assessment

The goal of this study with respect to LCA was to compute operational and embodied emissions of buildings. We consider the construction, maintenance and operation phases of the buildings, but exclude demolition and recycling processes. ~~In line with the state-of-the-art research,~~ The functional unit was chosen as one square meter area of dwelling over one year (1 m^2·year), and the lifetime of all the buildings was assumed to be 80 years (Ianchenko, Simonen and Barnes, 2020). LCAs were performed with Brightway - an open source Python library for advanced LCA calculations (Mutel, 2017).

To estimate the **operational emissions**, LCIA was conducted for the computed space heating demand for each building, where the specified heating source was matched against the processes in ecoinvent LCI database version 3.8, cutoff system model (Wernet et al., 2016). The foreground system for the **embodied emissions** was constructed based on the material composition dataset (Section 2.3) linked to the KBOB platform (Section 2.6).

Environmental performance for the climate change impact category is assessed via the 100-year time horizon GWP values of numerous greenhouse gases based on the IPCC report (Stocker, 2014). This LCIA method was implenented for ecoinvent environmental flows by Bourgault (2020). Final LCIA scores are expressed in kilograms of CO_2 equivalent (kg CO_2-eq) per square meter area and one year. Naturally, this analysis can be easily extended to other impact categories and LCI databases.

4. Case study

To demonstrate how the user inputs can be incorporated into the developed tiered model, we use a case study data that was collected from Swiss architects and planners (John, 2012). This dataset represents 12 relatively ~~sustainable~~ modern residential buildings constructed post 2000, and serves as a good case study to test the tiered model performance due to the differences in the selected buildings. The major advantage of this dataset is the availability of detailed information on every building's properties, components and material compositions. Among other things, this data includes annual add ventilation system

Table 2
Basic information on 12 Swiss buildings used in this model as case study (John, 2012)

	Canton	Construction year	Accommodation units	Built surface area [m^2]	Heating source	Energy standard
mfh01	Zurich	2012	111	2350	Electric heat pump water brine (343 kW)	MINERGIE (1) → Ref
mfh02	Schwyz	2011	2	190	District heating	MINERGIE-ECO (2) + describe as footnote
mfh03	Bern	2011	3	163	Electric heat pump water brine	MINERGIE-P (3)
mfh04	Zurich	2010	4	240	Electric heat pump water brine (16.7 kW)	SIA 380
mfh05	Zurich	2007	132	2218	Electric heat pump water brine (92 kW)	MINERGIE-P-ECO
mfh06	Bern	2006	3	777	Wood pellet heating (67.2 kW)	MINERGIE-P-ECO
mfh07	Zurich	2011	89	1810	Modulating condensating boiler (kW 200)	MINERGIE
mfh08	Lucerne	2011	6	375	Electric heat pump water brine (24.9 kW)	MINERGIE-P-ECO
mfh09	St Gallen	2008	4	135	Electric heat pump, air water (4.2 kW)	MINERGIE-P-ECO
mfh10	Zurich	2012	10	411	Near/ district heating from cogeneration	MINERGIE
mfh11	Bern	2012	22	665	Electric heat pump water brine (40.8 kW)	MINERGIE-P-ECO
mfh12	Lucerne	2008	10	168	Electric heat pump water brine (28.1 kW)	*not available*

space heating demands of the buildings and thermal transmittance values of the building components that are needed for the validation of the model results (see Figure 1). Additionally, the dataset contains information on the ventilation air exchange rates and the hot water demands for some buildings, which leads to higher quality estimates of operational emissions compared to the results of Buffat et al. (2017). The basic characteristics of these buildings are laid out in Table 2, and the details are provided in the SI excel document.

4.1. ~~Allocate~~ Building properties

To include the case study data as the user inputs, the first step is to allocate building properties to each of the case study buildings given its ID or geocoordinates (Figure 1). As a general rule, we expect this data to be available to the users of the developed tool. However, the given case study does not contain information that uniquely identifies the buildings, since it is part of the open access doctoral thesis, where the anonymity of the buildings needed to be maintained (John, 2012). Thus, in this paper we use a two step approach to find the building properties:

done

#floors ?

Step 1: Prompt the user to provide three of the building properties: the year of construction, its municipality and height. These building properties were chosen because they are typically accessible to the user, and are least likely to be measured wrong or be affected by the renovations over the building's lifetime.

Step 2: If the model fails to find a unique match and identifies a set of buildings instead, we employ the "least distance approach", where the model looks for a closest match of a building in terms of the provided building properties.

not shown

The 12 matched building and their properties are given in the SI excel file. → maybe we should not show the location of the 12 buildings?

4.2. Scenario assessment

Since renovations significantly affect the environmental impact of buildings (Hasik, Escott, Bates, Carlisle, Faircloth and Bilec, 2019; Itard and Klunder, 2007), we perform scenario assessment to estimate emissions related

Table 3
Maximum U-values for insulation scenarios.

renovation scenario	Max. U-Values, W/m^{2}K			
	Walls	Windows	Roofs	Floors
Standard	0.15	1.00	-	-
Efficiency	0.10	0.60	0.15	0.15

done
Minergie
Min-P

Table 4
Climate change impacts of various heating sources.

Heating source	Impact per unit of energy kg CO_2-eq / MJ
Electric heat pump (brine water)	0.033
District heating	0.00019
Wood pellet	0.013
Natural gas	0.065

not current scope
also possible: different setpoint T (as currently proposed for Ukr. war situation 18°C)

to renovations. In the following, we introduce two sets of scenarios, which focus on estimating the potential emissions savings. Note that in this paper the purpose of the scenario assessment is to showcase that the ~~tiered~~ model allows the users (building owners, policymakers, architects) to introduce various renovation scenarios to compare building emissions based on different renovation options for better informed environmental decision-making (see (Fishman, Heeren, Pauliuk, Berrill, Tu, Wolfram and Hertwich, 2021; Heeren and Hellweg, 2019; Mastrucci, Marvuglia, Benetto and Leopold, 2020) for possible renovation scenarios).

Adding insulation: A common practice in reducing the heating demand of a building is to reduce its thermal losses via additional insulation layers or replacement of the existing insulation with better insulation materials. In this work, we follow the study of Ostermeyer, Nägeli, Heeren and Wallbaum (2018) that considers standard and efficiency renovation scenarios based on building types. The former scenario leads to the resulting U-Value of the refurbished building components between the legal minimum (SIA 280) and the MINERGIE standard[4], and the latter aims at transitioning towards a passive-house, such as MINERGIE-P (see Table 3). Where in Tab 3? ~~Efficiency~~ ?

Changing heating source: In addition to the insulation changes, which affect both the operational and embodied emissions, the change in heating sources can be quite influential to reduce the operational emissions of buildings. For the given case study, the primary heating and hot water sources with their respective climate change impacts are given in Table 4. The only case where changing a heating source could make a difference is the natural gas heating, because it has a high impact per unit of energy used. As ~~the~~ district heating ~~heavily~~ depends on the location of a building, based on the second least environmental impact, in this scenario we introduce a change of natural gas to the brine water heat pump.

comparatively   the availability of   substantial

Done

[4]https://www.minergie.ch/de/zertifizieren/minergie/