Graphical Abstract

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Highlights

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Combined material-energy building environmental footprint model: assessment of future renovation scenarios

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ABSTRACT

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.
> Thus we develop a interface where this material data can be integrated with models estimating in-use demands, givign a final LCA of buildings.
> We further add scenarios to estimate the maintenance phase of the building as well.
> 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.
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1. Introduction

Nearly one third of total global final energy consumption can be attributed to the buildings and buildings 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 (Chastas, 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 surface models 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 age range (in Buffat et al. (2017) approach). This approach lead to low accuracy of the U-values. A more comprehensive analysis requires primary data on the material composition of the buildings components.

Material data obtained from building owners and architects can be helpful in modeling existing buildings stocks. John (2012) provided material compositions for 12 residential buildings in Switzerland and their life cycle assessment (LCA) impacts. This study contains rich level of detail in the material data due to the collected information from architectural sources; at the same time, it does not account for spatial and temporal site conditions. This resulted in higher reliability of the computed embodied impacts compared to the operational emissions estimates.

The aim of this study is to provide a model that pays equal attention to more accurate estimation of both embodied and operational greenhouse gas (GHG) emissions of residential buildings. To this end, we (1) improve the GIS-based bottom-up energy demand model from (Buffat et al., 2017) by converting it to a interface that allows integration of external material data sources and user inputs; (2) replace the generic probabilistic U-values with building specific material composition data (John, 2012); (3) incorporate life cycle inventory (LCI) data to assess building impacts from operational emissions, given more precise space heating estimates, and compute embodied emissions; (4) compare various renovation scenarios and their potential benefits and impacts, (5) finally, validate U-values, space heating demands and embodied GHG emissions with reported data. The primary output of this work is a interface that allows data inputs from users in case material data is available, and where different scenarios can be tested to estimate the LCA of buildings. Note that throught this paper, the LCA of building includes the construction, maintenance and operational phases of the building (and not the demolition and recycling phase).

2. Methodology

This section outlines the methodology developed in this paper, for quantifying the operational and embodied impacts of buildings. Figure 1 provides and overview of the model and data, which comprises of two main sections; first one showcasing the data and methods used in the model by Buffat et al. (2017), and the second one showcasing how the data inputs on the material composition and building properties can help in estimation of the overall LCA of the buildings. As shown in this figure, multiple data parameters like the building data (building area, construction year, heating systems, and the newly added material composition data) and site data (temperature, radiation, etc.) is used to estimate the final building overall emissions.

In the following subsections, we list all the different data parameters used in the model with their respective data sources, (Section 2.1) and then we explain how some of these data parameters, e.g. the material composition data, are further processed (Section 2.2). Next, we describe our model explaining how to improve the bottom-up model of Buffat et al. (2017) to perform the LCA of buildings(Section 2.3). The detailed steps to conduct the complete analysis are provided in Supporting Information (SI) Section XX, whereas the code to reproduce the results is given as a GitHub repository[1].

2.1. Data Description

The data used in this model can be divided into five main categories, as listed below. The overview of datasets with their sources and their data parameters can be seen in Table 1 (detailed in Table 4 and SI Table 1).

[1] https://github.com/rhythimashinde/building-model-shef

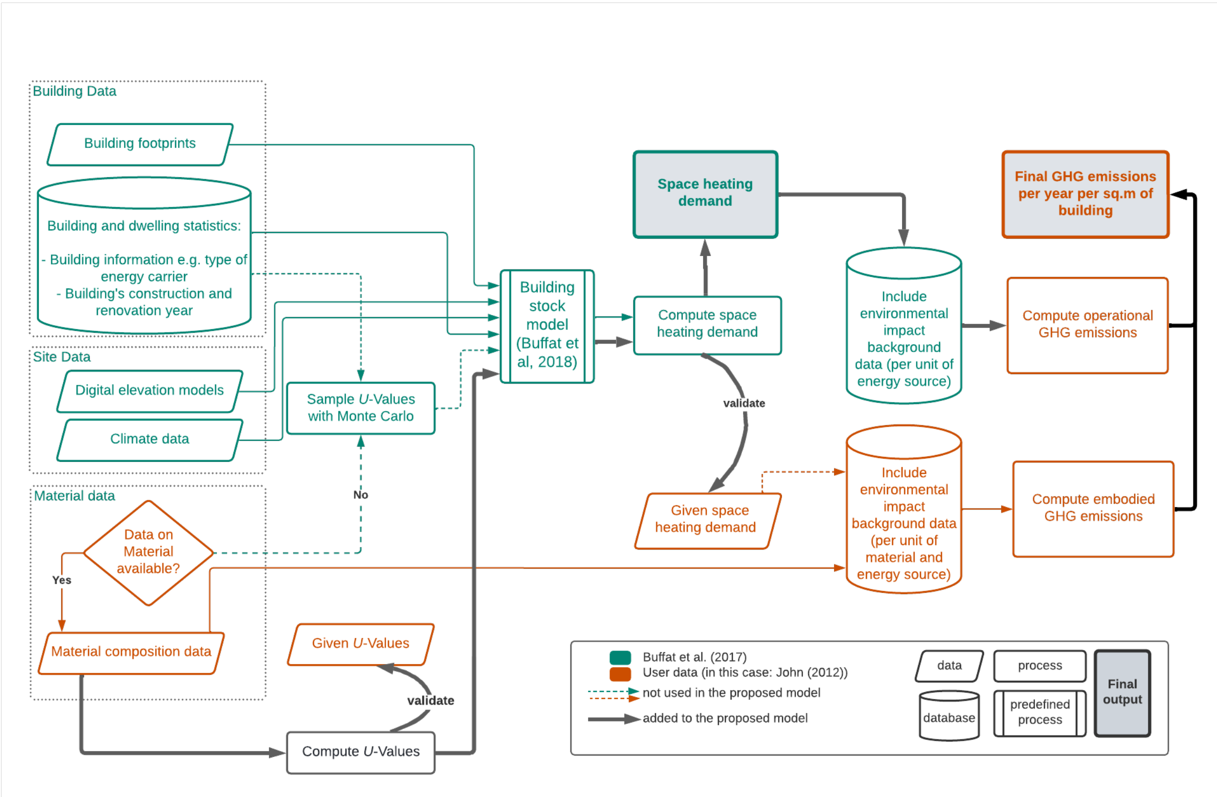

Figure 1: Methodological approach for material-data integration and validation

Building Data: This data includes the information on each building system (e.g. on the construction, renovation phases and its physical built e.g. the construction year, number of floors, building location, roof shape, area, heating location, etc.). In case of Switzerland, this data can be obtained from the existing building datasets such as Federal Register of Building and Dwelling (FRBD) (FSO, 2022). FRBD contains detailed information for the residential buildings in terms of their (1) physical parameters e.g. the number of floors, the building size, the roof type, window details, type of energy carrier, etc. , (2) construction and renovation details e.g. when was it constructed, renovated, etc. , and (3) energy related information e.g. the energy carrier for heating and warm water.

Material data: This data includes all the information on material composition and amounts in the building e.g. the thickness of the concrete in the walls, the layers of insulation, etc. To enable the use of detailed & updated data on material composition (if available), we transform the model so that it can be used as a interface for architects and building owners in such a way that users can update the existing building datasets or add new information to the datasets. In particular users can enter or modify data on the building properties and the material composition of the building. In this paper we use a specific dataset from John (2012) to illustrate how material data can be specified and used in the model. We also introduce a new dataset of thermal conductivities of different materials. The material data provided by John contains the materials used and their thickness, especially for these components of the building: Façade, Inner walls, floors, ceilings and roofs. The material data is needed for the calculation of the embodied impacts and to estimate U-Values, as input to the energy demand model.

Site data: This data comprises of the building site information and parameters affecting buildings' environmental impact e.g. the temperature, radiation, digital elevation/ shading effect, etc. This is important dataset for estimating the emissions of a building as the building's location and physical environment ('site') affects the outdoor temperatures and conditions, affecting the heating demand of the building. Here, we use the weather and radiation data from Swissmeteo aggregated on a monthly basis. Additionally, we use the data from the Swiss Federal Office of Topography (swisstopo) (cite) which provides the location of the building to maximum accuracy, and this helps in estimating the building's neighborhood and its impact on the shading effects (Buffat et al., 2017) furthering the effect of the outdoors on the final heat demand. The swisstopo also gives the physical 3D structure of the building, allowing to derive the building's topographic features like the roof structure, etc.

Environmental impact (background) data: This data mainly comprises of the life cycle inventory (LCI) i.e. the emissions factors of the different material and energy sources used in the building during its different phases (of construction, maintenance, and operations). In this paper, for the material impact factors, KBOB (Koordinationsgremium der Bauorgane des Bundes) [2] is used, as this dataset contains fairly accurate estimations of impacts of (construction and insulation) materials used in buildings components (e.g. facade, roof, windows, etc.) for Swiss residential buildings. For the energy sources, we use ecoinvent 3.6[3] which helps in calculating the impact associated to each material and the heating system energy source found in the buildings. We use this data towards calculation of the final Greenhouse-gas emissions (GHG) emissions of the buildings using the IPCC GWP 100a LCA method (cite).

Validation Data: This data includes the measured annual heat demands of the building (operational emissions), the thermal resistance of the building components (U values), and the total greenhouse gas (embodied) emissions of the building from John's data for validation, which helps in finally evaluating the model developed here.

2.2. Data Processing

The data entered by users (e.g. material data from John) need to be preprocessed to match the other types of existing datasets in the model (e.g. the FRBD building data). In this paper, we use case study of 12 Swiss buildings to showcase the data processing steps to the final results. Figure 2 shows all the data parameters used from the different data and models in this model and arranged together in this paper. Following steps are used for preprocessing in this case study:

1. The first step is to match the buildings across various datasets so that all the building parameters can be linked to the same building ID. For the same, we match the characteristic building parameters, which are: the year of construction, canton & municipality, building area, height of the building, and occupancy. These parameters are chosen because they are provided in most of the databases and are least likely to be measured wrong or affected by the renovations or changes in the building over its lifetime.
2. If we could not find a perfect match of the buildings a "least distance approach" is applied (discussed in SI Section 2) for finding the closest match of building across different datasets. In our paper, we match the 12 buildings from John's data to the FRBD dataset to allocate the material data to the buildings. The mapping of the buildings across datasets is shown in SI Table 2.
3. After material data is added to each component of the building, based on the material composition of each component, the respective U Values are calculated (Section 2.3.2).
4. All these U Values replace the generic U Values from Buffat's model. Finally the model is run to calculate the new heat demand.

2.3. Model

In this section, we showcase how to input the data for the Buffat model by including the material composition of the building (Section 2.3.1). This helps in estimating the U Values of the components of the building (e.g. the walls, the windows, etc.) which calculates the energy lost through the building's components. By including the other data parameters like the building and site information, with the derived U Values, we can estimate the heating demand of the buildings better (Section 2.3.2). Finally, with an accurate material composition of the building, we are able to estimate the embodied impacts better and thus we are able to perform LCA of the buildings (Section 2.3.3). To showcase the impacts of maintenance phase of the building, we introduce few scenarios of renovation and check the impacts on the LCA of building (Section 2.3.4).

[2] https://www.kbob.admin.ch/kbob/de/home/die-kbob/plattform-oekobilanzdaten-im-baubereich.html
[3] https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-6/

Table 1
All datasets used in the model: An overview

Data category	Dataset (Sources)	Data parameters
Building property data	Building information (FRBD, 2018; John, 2012)	Type of construction
		municipality ID
		Canton
		Geocoordinates (location)
		Year of construction
		Number of floors
		Number of accommodation units
		Built surface area (m^2)
		Altitude h [m]
		Energy reference area (m^2)
		Heating source
		Attic (present or not) and the size
	LIDAR data	Components of the building (and their geometric shapes and sizes)
Building material composition data	Material composition for construction and insulation in building (John, 2012; User inputs)	Materials used for Façade
		Materials used for inner wall covering
		Materials used for inner wall construction
		Materials used for floor covering
		Materials used for ceiling covering
		Materials used for roof covering
		Materials used for floor construction
		Window specification (materials and single, double or triple glazing)
Building material property data	U values	Wall U value
		Roof U Value
		Ceiling U Value
		Floor U value
		Window U Value
Site data	Building structure (Swisstopo)	Roof type
		Location coordinates
	GIS/ geological data (Swissmeteo)	Solar irradiation data
		Weather data (Temperature on monthly basis)
Environmental impact (background) data	LCI databases (ecoinvent, KBOB)	Ecoinvent3.6 (energy emission factors)
		KBOB (material emission factors)
Validation data	Energy demand and embodied emissions (John, 2012)	U values
		Heat demand
		LCA

2.3.1. *User Input*

The model developed here allows users to input or overwrite the data for one or many data parameters in the model at the same time e.g. the material data for various building components. If no entry is made, the model takes default values. The Table 2 shows an example of a building (mfh02) which is added as an input to the existing case study of 12 buildings. The detailed data on the buildings can be found in SI Table 2-5. Following steps shows the steps for how the input interface is used to input different types of data and convert them into dataset so that they can be included in the model.

1. The interface asks for input to list the building details, which includes the following:
    - List the building basic properties e.g. the building construction year, height and area of the building, etc.
    - List the building components e.g. the number of windows, walls, etc.
    - List the component material composition and details e.g. the materials used in each wall and their thicknesses, etc.

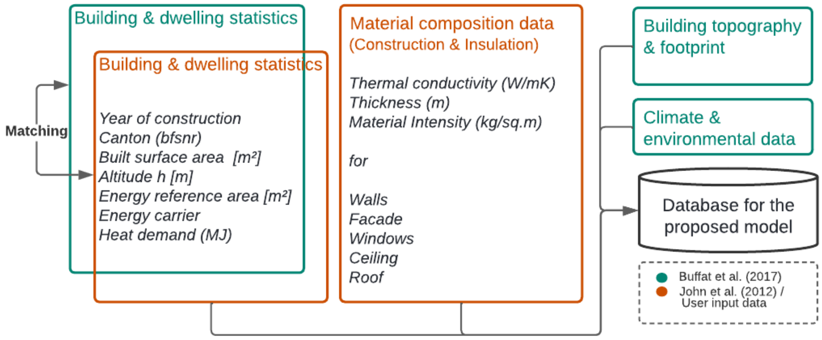

Figure 2: Data parameters and datasets used in the current model

Table 2
Example of a property table (user / data input) for building mfh02

material	Area (m²)	Given U Values	5-layer insulated (glass wool) wood panel	Bitumen waterproofing membrane GV2	Cement cast plaster floor	Concrete floor slab
floor	190.95	0.197			0.04	0.22
ceiling_1	149.1				0.05	
ceiling_2	396.9		0.165		0.05	
external_wall_1	372	0.114				
external_wall_2	260	0.127		0.003		
internal_wall_1	128.7					
internal_wall_2	73					
internal_wall_3	339					
roof	287	0.105				

- List the U Values of the materials used above (if known).

2. Based on the information collected above (an example in the Table 2 shown below, we create the material database for each component. Then we also allocate it to their thickness and U Values (we provide a lookup table for the U values of different materials, if they are not provided from the database created).
3. This helps to generate a building 'dictionary' [4], with their components and their associated properties linked and stored in the model.
4. As soon as new building dictionary is added, we calculate new default values for thermal conductivity (U Values) based on the building typologies (construction, renovation year, location of the building, etc.).
5. In case, the new input building misses the information of the components, these default values are allocated to the building.

2.3.2. Heating demand

Table 3 shows all the U values which are updated for each building in this model. These values are estimated in Buffat's model based on the construction and renovation years of the building (Wallbaum, Heeren, Jakob and Martius, 2010) which means that all the buildings in this model which are constructed and renovated in the same duration get the exact same values. Thus our model works on this gap by trying to allocate a more correct estimation of the U Values by using more accurate material composition of the buildings.

Each component of the building, e.g. the wall, roof, etc., is built of many layers of different materials with varying thicknesses. Each material has its own thermal conductivity. Based on the material used, their thickness and their

[4] https://www.w3schools.com/python/python_dictionaries.asp

Table 3
U values and the associated components allocated in Buffat et al. (2017)

Notation in the building stock model	Component of building
u_fe	Floor against outside air
u_fu	Floor against unheated spaces
u_fg0	Floor against earth with component heating
u_wg0	wall to ground
u_ru	Ceiling against unheated space
u_we	Wall against outside air
u_wu	Wall against unheated spaces
u_wh	Wall against adjacent heated space
u_re	roof against outside air

thermal conductivities, the U Value for each component of the building is calculated using the equation 1. Note that if we have multiple components of same type, e.g. multiple walls, for the sake of model simplification, we select the minimum U values for that component of the building (an example for mfh02 components with the materials' details and calculation of final U Values is showcased in SI Section 3).

$$U_c = 1/(R_1 + R_2 ... + R_n) \tag{1}$$

where
c= component of the building (e.g. wall)
R_i *= t/K*
i = the material of the component (.g. cement in the wall)
t = thickness of the material
k = thermal conductivity of the material

For estimating the final heating demand, in our model we use the effects of various types of data listed in the Section 2.1. The building and site data helps in understanding the effects of physiological building aspects like the building area, roof structure, etc. to estimate the energy needed to heat up the space. Combining this with the material related impacts e.g. due to the insulation of the building, updates the heating space demand for the building. This put together with the environmental impact (LCI) data helps to calculate the final impacts for the building. As the input data in our model is updated e.g. the material composition and the U Values, the new input data is passed to the existing Buffat's model updating the final heating space energy demand.

2.3.3. LCA

For Life Cycle Assessment (LCA) of the building, in this paper, we consider the construction, maintenance and the operational phase of the building (and not the demolition and recycling). We use the IPCC GWP 100a method, which calculates the greenhouse gas emissions (kg CO_2 eq.) for the buildings. We use the brightway interface [5] to allocate the final impact factors to the material and energy sources of the building. All materials of the building are coupled with background LCI data from ecoinvent and KBOB to calculate the embodied impacts of each component and building. For the operational phase, the calculated heat demand and the data on heating systems were also combined with the background LCI data to estimate the LCA. While we only calculate the GHG emissions, the tool can be modified to calculate other environmental indicators.

2.3.4. Scenarios

As the renovations have a significant impact on the building-related emissions (in their lifespan) , two sets of scenarios are introduced in this model to estimate the potential savings in the emissions of the building. In our model, scenarios directly update the building information data which enter the model and thus update the final operational and/or embodied emissions. The scenarios are explained below with steps for model modifications.

- "Insulation" scenario: A common practice to reduce the heat demand of the building (and thus the operational emissions and also the energy bills) is to improve the thermal resistance of the buildings. This is usually done by

[5] `https://brightway.dev/`

insulating the buildings further with adding insulation layers. We consider two types of insulation layers addition following the refurbishment scenarios laid out by Ostermeyer, Nägeli, Heeren and Wallbaum (2018):

1. Standard refurbishment: to transition the resulting U-value of the refurbished building components between the legal minimum (SIA 280) (cite) and the MINERGIE standard*Reference to Minergie standards [6] which means the U Values for walls < 0.15 W/(m^{2}K), for windows < 1 W/(m^{2}K).
2. Efficiency refurbishment: to transition towards a passive-house or MINERGIE-P which means the U Values for walls approx. 0.10 W/(m^{2}K), for roof < 0.15 W/(m^{2}K), for floor <0.15 W/(m^{2}K), for windows < 0.6 W/(m^{2}K)

- Change in heating source: This includes the transition to the next best heating source based on their environmental impact. The following order is followed for the upgrade of the heating source - whever possible the heating system is upgraded to a (brine water) heat pump.

The first two scenarios are applied based on the initial build of the building. In other words, lets take that a building is already a MINERGIE, then the standard refurbishment wouldn't add any benefit in terms of the insulation to the building, and thus the efficiency refurbishment is used. The protocol followed here is based on the building archetypes defined by Ostermeyer et al. (2018) based on the age and initial build of the building (important building component and the important building material). Similarly, the heating source is upgraded as per the existing heating source.

Also, the users of the interface developed here (e.g. building owners, policy makers, etc.) can make dummy datasets to develop scenarios for building renovations (e.g. changing further the insulation material of the building), to check the changes in the building impact. Note that these scenarios are performed for illustrating the capabilities of the tool developed here. All buildings in Table 4 are relatively new and well insulated, and in reality they would probably not be the candidates for the energy related renovations.

3. Results and Validation

In the following section, based on the methods discussed above, the results are laid out for the estimated U values (section 3.1) and heat demands (section 3.2) for impacts in operational phase of (for case study of 12 Swiss) buildings are laid out. Then, to incorporate the impacts of all the construction, maintenance and operational phase, the LCA results with the scenario results are discussed (Section 3.3 and Section 3.4). Before we discuss the results, the basic characteristics of these buildings are laid out in the Table 4 below (detailed in SI Table 1).

3.1. U values

In this section, we present how the U values calculated in our model vary compared to the reported U values for the 12 swiss buildings. The following Figure 3 show an example with the calculated (in our model) and reported U values (from John's data) for two building components (roof and external walls) of few buildings. As can be seen in the graph, the calculated and the given values are not significantly different, which confirms the U values calculation implemented in the model. In the SI Table 4 we also show these U values for all the building components for all the buildings, compared to the reported U Values and the U Values which are estimated for these buildings by the Buffat et al. (2017) model.

3.2. Heating demand

After allocating the U values for the building components to the buildings, the heat demands are updated using the Buffat et al. (2017) model. The following Figure 4 shows the calculated vs measured heat demand results. For comparison, in the same graph we also add the "old" calculated space heat demand results (with the simplified estimation of U values in Buffat et al. (2017)). As shown further in the Table 5, the current model shows a very high improvement in the final heat demand quantification compared to the previously simplified U values. the buildings with highest improvement in relative error (mfh 03, 06 and 08) are also those where the U Values changed most due to the new quantification of U values and introduction of material composition. Also note that these are the buildings with some of the highest estimated heating demand. This provides a scope for our model to correct the "default" u values for these building typologies, improving the estimations of buildings' energy demands. Note that although the relative error reduces with the new model, the high error for some of the buildings (compared to the measured values)

[6] https://www.minergie.com/

Table 4
Basic information on 12 Swiss buildings used in this model (as case study to showcase model results)

	Canton	Construction year	Accommodation units	Built surface area [m²]	Heating source	Energy standard
mfh01	Zurich	2012 (8022)	111	2350	Electric heat pump water brine (343 kW)	MINERGIE
mfh02	Schwyz	2011 (8022)	2	190.2	District heating	MINERGIE-ECO
mfh03	Bern	2011 (8022)	3	163.4	Electric heat pump water brine	MINERGIE-P
mfh04	Zurich	2010 (8021)	4	240	Electric heat pump water brine (16.7 kW)	SIA 380
mfh05	Zurich	2007 (8021)	132	2218	Electric heat pump water brine (92 kW)	MINERGIE-P-ECO
mfh06	Bern	2006 (8021)	3	777	Wood pellet heating (67.2 kW)	MINERGIE-P-ECO
mfh07	Zurich	2011 (8022)	89	1810	Modulating condensating boiler (kW 200)	MINERGIE
mfh08	Lucerne	2011 (8022)	6	375.3	Electric heat pump water brine (24.9 kW)	MINERGIE-P-ECO
mfh09	St Gallen	2008 (8021)	4	135.15	Electric heat pump, air water (4.2 kW)	MINERGIE-P-ECO
mfh10	Zurich	2012 (8022)	10	411	Near/ district heating from cogeneration	MINERGIE
mfh11	Bern	2012 (8022)	22	665	Electric heat pump water brine (40.8 kW)	MINERGIE-P-ECO
mfh12	Lucerne	2008 (8021)	10	168.75	Electric heat pump water brine (28.1 kW)	

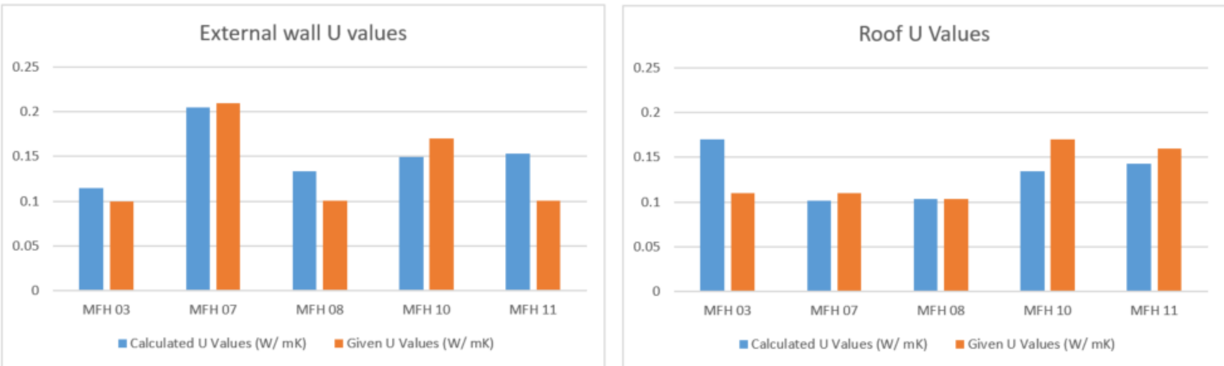

Figure 3: Results of U Values for 5 example buildings: calculated (in our model) vs reported by John (2012)

exist due to multiple reasons including the user behavior, etc. which is not included in the model currently (discussed more in Section 4). Also, it is important to note that the measured data referred to one particular year, which may not be representative for longer time periods.

3.3. LCA results

Allocating the material impact factor per material used in the building components, we estimate the embodied emissions of the building. This database of the material impacts for the 12 Swiss buildings used in the case study here is shown in the SI Section 5. The estimated embodied GHG are then added to the operational GHG (calculated via space heating demand estimated in the above Section 3.2 above), to estimate the total GHGs for the building. The Figure 5

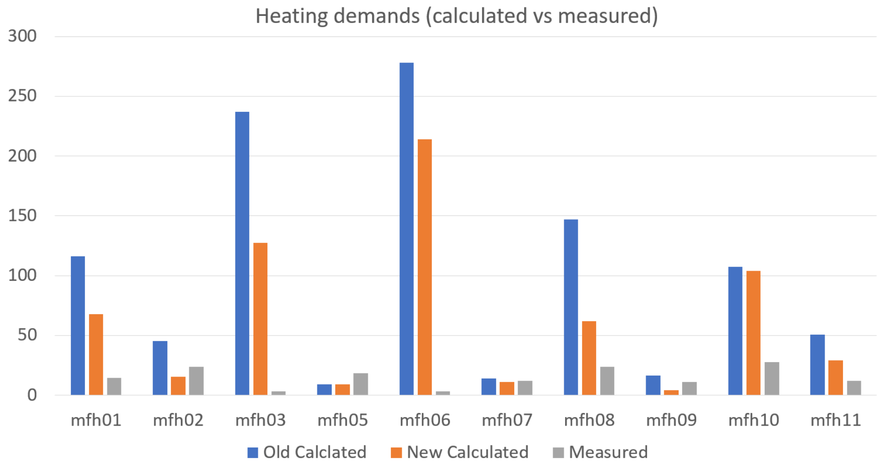

Figure 4: Heat demand estimation of the simplified (old) approach by Buffat et al. (2017) (left bar column), the updated model using accurate material specifications of each building (middle bar column), and reported values by John (2012) (right bar column)

Table 5
Relative errors [7] for the models in estimation of space heat demand

Building	Decrease in relative error	Relative error old	Relative error new
mfh03	33.22	70.79	37.58
mfh06	19.43	83.24	63.81
mfh08	3.55	5.14	1.58
mfh01	3.37	7.08	3.72
mfh11	1.81	3.27	1.47
mfh02	0.54	0.89	0.35
mfh10	0.11	2.86	2.75
mfh07	0.06	0.15	0.09
mfh12	0.00	1.00	1.00
mfh05	-0.01	0.50	0.51
mfh09	-0.15	0.46	0.61
Average	**5.63**	**15.94**	**10.32**

shows the Greenhouse Gas (GHG) emissions calculated annually per metresquare of the different buildings. The results show that the LCA of the buildings is rather high for the mfh02 and mfh06. One of the reasons explaining this could be the ratio of the building surface area per sq.m being the highest for these two buildings (96 m^2/ accommodation unit and 259 m^2/unit, respectively).

3.4. Scenarios

For showcasing how the model works with various scenarios, we have introduced two scenarios for two buildings mfh07 and mfh10 as they have a natural gas as a heating system which can be improved further (scenario 2). We keep the same buildings for further improvements in insulation (scenario 1) to study the effects of different scenarios on the same building. The changes as per the scenarios in the existing buildings' parameters e.g. the walls' insulation, or the heating systems, can be seen below in the Table 6.

Scenario 1- Insulation: For the first scenario of adding a layer of insulation, a new insulation material is added in the building walls which is not already present to effectively change the thermal conductivity of the walls and reduce the U values. This affects the LCA of the building in two ways: the additional material increases the embodied impact of the building, while the additional insulation reduces the energy impact (usage) for heating the building. As shown

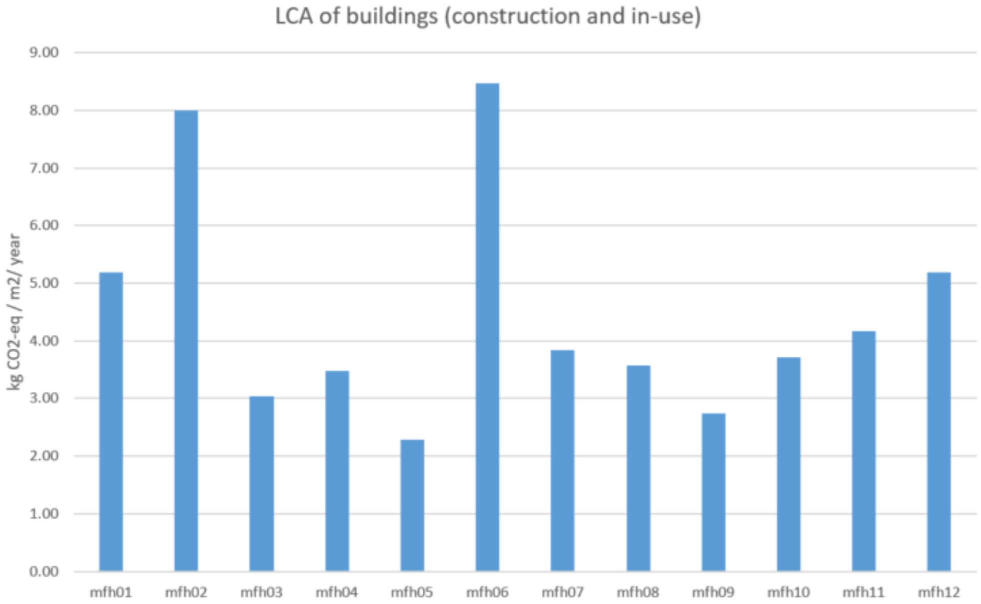

Figure 5: LCA (Greenhouse gas emissions) for all the buildings, split by the embodied and operational emissions. The lifetime assumed for all buildings was 80 years.

Table 6
Changes in building parameters introduced as per the scenarios

	Scenario 1: Insulation				Scenario 2: Heating	
	Old U Value for walls	New U Value for walls	Insulation material	+Material intensity ($kg/m^2/year$)	Old heating source	New heating source
mfh07	0.116	0.050	rockwool insulation	0.089	Natural Gas	Heat Pump
mfh10	0.16	0.033	cellulose fiber	0.468	Natural Gas	Heat Pump

in Figure 6, the insulation scenario shows for both the rockwool insulation in the mfh07 and cellulose fiber in mfh10 that the insulation is not very effective way for reducing the impacts. It should be noted the energy benefit of adding insulation is only about 5%, comparable to the second scenario of heating system change.

Scenario 2- Heating source change: For change in the heating source, we chose to convert the natural gas systems in the two buildings to brine water heat pumps, as they have low impact (district water incinerators have even lower impacts, but they can only be installed based on the location of the building). Figure 6 shows that the change in energy sources help in always reducing the impacts of the building. It should be noted that these are MINERGIE buildings with a very low impact already, and thus the change in the heating source or insulation doesn't necessarily show an improvement, but for other buildings, the case might be different based on their initial construct).

4. Discussion and Outlook

Takeaways and highlights from the model :
> Considering the results, for the case of the 12 buildings (new energy-efficient buildings, only around 10 years old), operational emissions rather low, so relatively the embodied emissions clearly show to have a significant impact.
> The method improved the energy estimations for all of the buildings (still greatly deviating for the MINERGIE-P buildings, which have very low operational emissions)
> The method proposed here presents an improved way of calculating the LCA for the buildings, with the possibility for integrating data provided by users. Tiered approach allows for large scale modeling while allowing for detailed assessment if data is not available.
> We can also integrate data from other research in different regions, e.g. an extension of our study can allow integration

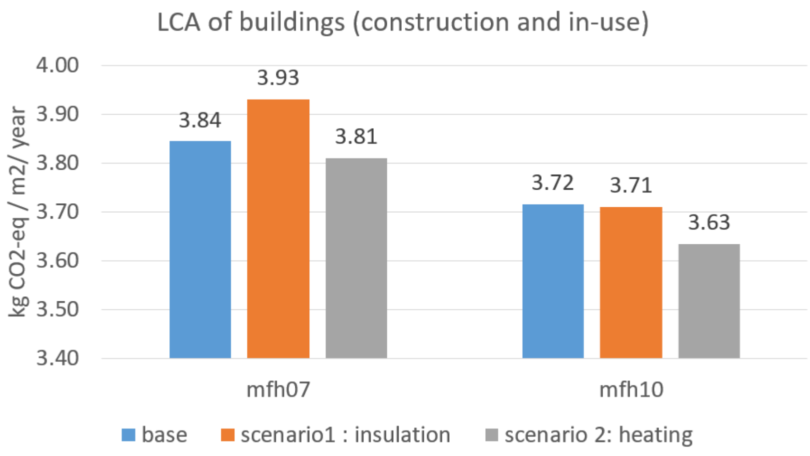

Figure 6: Scenario results: LCA (GHG) for two of the buildings (see Table 6 for Scenarios)

of approaches like Kleemann, Lederer, Aschenbrenner, Rechberger and Fellner (2016), which used construction data in combination with on-site investigations to characterize material composition of buildings in Austria; as well as Gontia, Nägeli, Rosado, Kalmykova and Österbring (2018), who created a material intensity database for residential buildings in Sweden that is based on architectural data and densities of construction materials. > Thus this is a truly bottom-up model while in comparison with other bottom up models (A detail analysis of bottom up model here Trigaux, Allacker and Debacker (2021))
> We also propose a framework to upscale the model by better estimation of U Values (even with missing material data) (Figure 7)
> Results
> scenarios

Limitations and improvements of the model :
> Uncertainties in thermal conductivity for similar materials, but still good results in figure 4
> Electricity consumption and hot water source not included in LCA - but can be
> Currently only monthly scale of temporal data is used in the model right now, and this can be modified for different scenarios like solar
> User behavior is not included

5. Conclusion

> Buildings are high emitters, in their construction, maintenance and renovation phase.
Though these phases are well estimated across various studies, they are not always well connected to each other e.g. the materials impacting the embodies emissions, also affect the final operational emissions
> Our model creates a interface and a data pipeline to integrate the data from users or studies to better estimate the LCA of buildings.
> It also allows estimating LCA better for buildings with missing data.
> Our study shows significant improvement in the energy estimations compared to a high resolution energy space heating demand model (Buffat's)
> It also shows that not all renovations affect the buildings for lower environmental impact when both the energy and material emissions are considered together
> There is a possibility to improve this model further with better data sources from electricity and heating water sources, and user behavior.

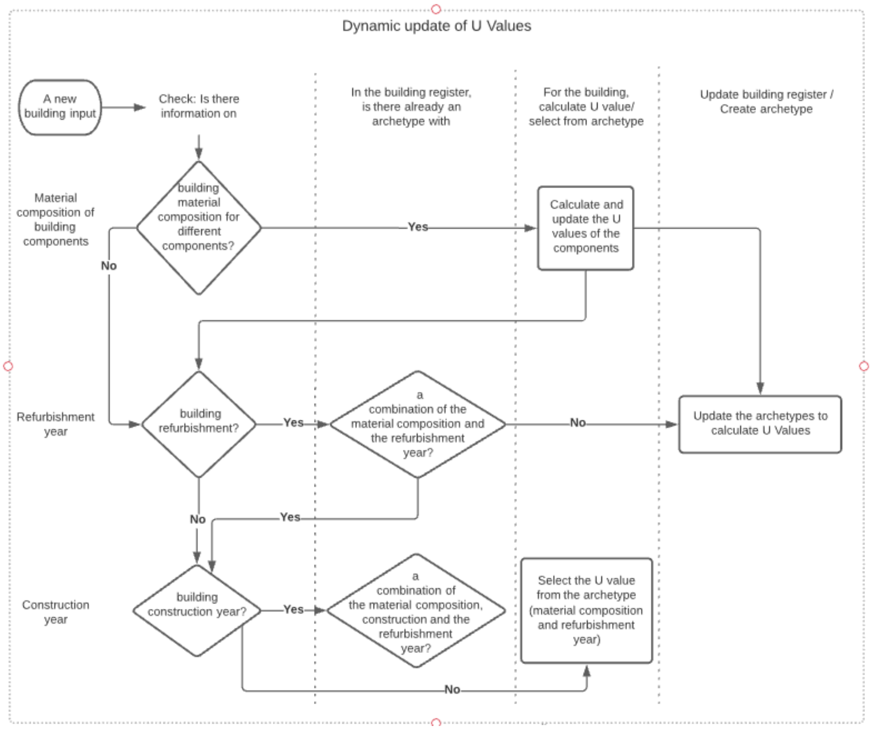

Figure 7: Framework to allocate U Values even with missing material data

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Authors contribution

All authors contributed to the presented study in conceiving and designing the analysis, and have reviewed and given approval to the final version of the manuscript. S.H. proposed the idea for this study and provided feedback throughout the project. R.S. conducted literature review, set up the models, performed the analytic calculations, the numerical simulations and drafted the paper. A.K. helped in writing and reviewing, and also contributing towards the LCA calculations in the model. All authors contributed to the writing of the manuscript. S.H. supervised the project.

Associated Content

Supporting_Information.pdf
Page 1-10: Data preprocessing and description details, Page 11-13: Method and choice explanation, Page 13-24: Detailed and additional results on different consumption categories and household properties.
Complete Code available on `https://github.com/rhythimashinde/building-model`

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