TBD
- Tiered approach presented in Fig 8 is to show how to allocate new default values when the data is insuffieint, adding it in methods can overload the methods section
- Open question

- I think we need to describe the tired approach a bit better. Fig 8 was not very clear and I tried to simplify (see attachment “tieredapproach”. This should be integrated then in the methods section. One open question is how to assess the embodied emissions when only default values are available (tbd).

TBD: We would need a matching everytime, the detailed method for the "imperfect" matching is anyways described in SI.

- The matching algorithm was only relevant for the John data, but for a regular user this would not be relevant. Therefore, I would move this part to the SI.

Done

- The part where you describe the user input is very cryptic. I suggest you rewrite this, move Fig 3 to the SI and insert in the main paper a table where you have the various parameters that can be modified as well es example entries (and maybe the previous default values) for your 12 buildings (in the columns)

Done

To review table (with Sasha)

- Table 1 is better than before, but I am still a bit puzzled as I think it is not complete (does not include the parameters you need for modeling, e.g. the heating system in the building property data, the building geometry derived from the Lidar data (which I assume also gives the surfaces of building components to you), or the list of u-values for materials, which would be another row. Also, I suggest to start with building property data, then with material data (which is also building data), then material property data (which are the u-values), then site data…

Fixed

To review further with Sasha

- You need to be careful with terminology – in the LCA part you often use wrong terms, confusing e.g. inventory and impacts. Maybe Sasha can also help you there in the next “iteration”. For the impacts, you chose to only look at GHG (which is fine), but we should be careful then calling this a full “LCA”. The easiest solution would be to say that you illustrate the model application here with this one impact category, but others can be added in a similar fashion.

TBD

- The u-values look good, but the heat demand predictions are for some buildings still much higher than the reported data. For a minenergy P buildings, one needs to show that predicted energy demand is much lower than what we get for getting the label. This makes some of the results implausible and we need to check what happened there.

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

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Keywords:
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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 tool 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).
Done
depends on case
> scenarios show that energy source chnage is effective but insulation addition is not always as effective to save building's impacts. XX
XX

↳ you had rather new buildings, for older ones this would look different

1. Introduction → nice!

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, or~~ *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 more energy efficient appliances, better insulation ~~materials~~, 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).

have you considered electricity use of appliances? If not (and that would be in line with previous work) delete

Done

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 factors, such as income, fuel prices, technological advancements, and others. However, top-down models do not

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e.g.

Done

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 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 ~~finer~~ building geometries and ~~better estimate~~ accurately 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.

Done

Done

~~For instance,~~ 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.

Done

The aim of this study is to provide a ~~framework~~ model that pays equal attention to more accurate estimation of both embodied and operational emissions of residential buildings, ~~and apply it as a case study for Swiss 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 tool 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) ~~(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) ~~(4)~~ compare various renovation scenarios and their potential benefits and impacts; 5) ~~(5) finally,~~ validate U-values ~~and space~~ heating demands with ~~measured~~ recorded data. The primary output of this work is a tool 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).

Done

Done

and embodied GHG emissions

GHG

provides an overview of the model and data.

Done

2. Methodology

quantifying

Done

This section outlines the methodology developed in this paper, for ~~more accurate estimation of the~~ quantifying operational and embodied impacts of buildings. Figure 1 ~~showcases this methodology, 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 footprints, construction year, ~~etc.~~) and site data (temperature, radiation, etc.) is used to estimate the final building overall GHG ~~emissions~~.

Color legend?

it meant building area..
fixed

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 ~~showcase~~ describe our model explaining how to improve the bottom-up model of (Buffat et al., 2017) ~~such that it takes the processed data as an input and also further estimate~~ 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].

Done

Done

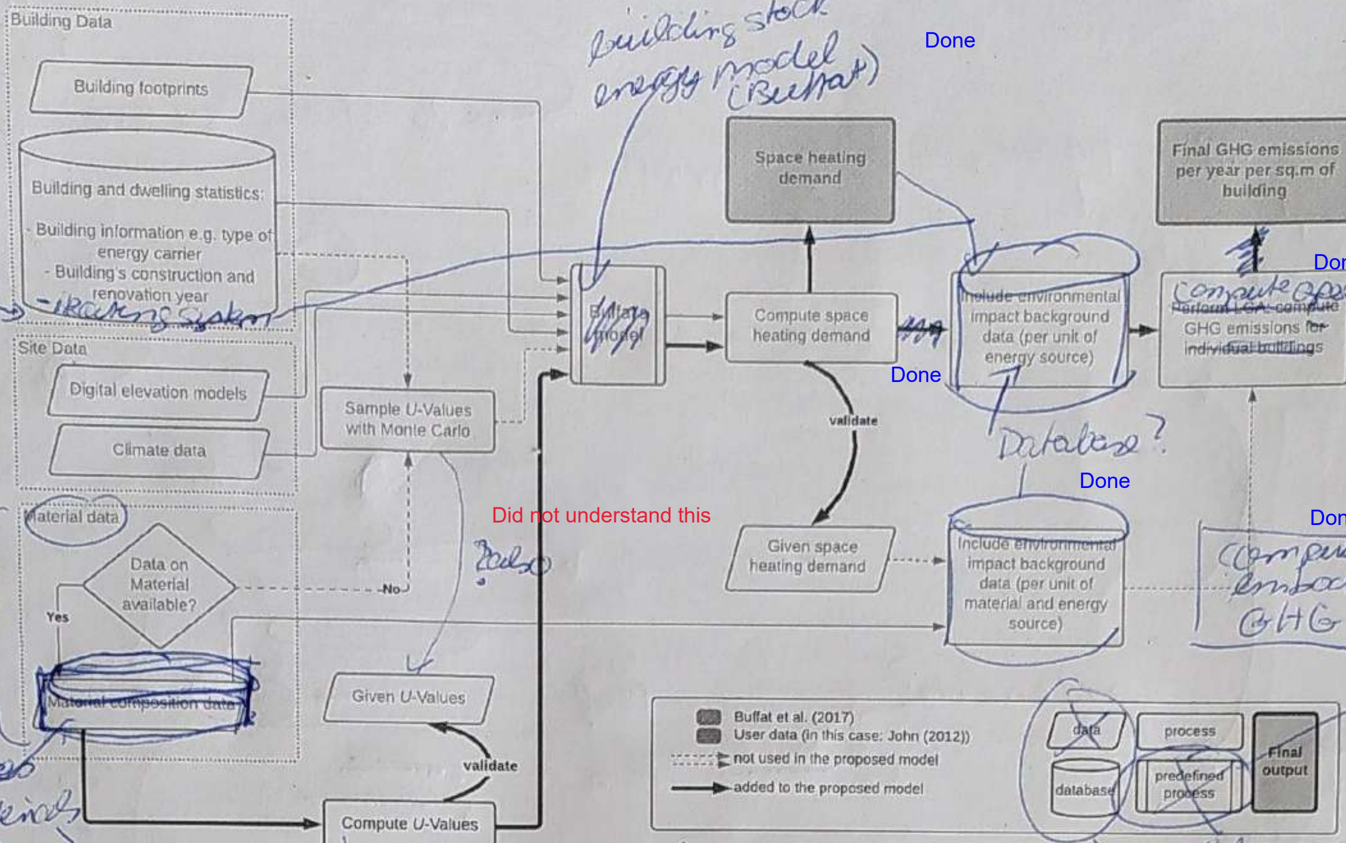
Done

heating system and newly also specific material composition data

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 data ranges in Section SI XX).

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



material data is also Building data (-> more Material box into building box)

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

Would like to introduce material data separately as it is processed separately

renovation year, each building, system, Done

Should we not give example here? or just call "system

Building Data: This data includes the information on ~~buildings construction, renovation phases and its physical built e.g.~~ the ~~construction year, number of floors, building location, shape, area, heating location, etc.~~ Such data ~~for Swiss buildings~~ 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.

in the case of Switzerland Done

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.

Done and amounts in

Material data: This data includes all the information on material composition ~~of~~ 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 tool 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

Sorry, cant read this

list all data you need ... year of last renovation ?

Table 1
All datasets used in the model: An overview

Data category	Dataset (Sources)	Data parameters
Building data	Building information (FRBD, 2018; John, 2012)	Type of construction
		bfsnr
		~~Canton~~ location (we know more than the canton)
		Year of construction
		Number of floors
		Number of accommodation units
		Built surface area [m]
		Altitude h [m]
		Energy reference area [sq.m.]
		Attic details
Site data	Building structure (Swisstopo)	Location data
		Roof type
	GIS/ geological data (Swissmeteo)	~~Weather~~ data → specify!
		Radiation data
Building material composition data	Material composition for construction and insulation in building (John, 2012; User inputs)	Materials used for construction
		Materials ~~used for~~ Façade
		Materials ~~used for floor covering & construction~~
		Materials ~~used for~~ ceiling covering
		Materials ~~used for roof~~ covering
		Windows ~~construction details~~
Environmental impact ~~(background)~~ data	LCI ~~databases~~ background data (ecoinvent, KBOB)	Energy ~~impact factors~~()
		Material ~~impact factors~~(KBOB)
Validation data	~~Energy demand and~~ embodied emissions ~~(John, 2012)~~	U values
		Heat demand
		LCA

Done Done Done Done Done Done Done

Lidar → geometry surfaces of building components?

property

and amounts (thickness surface?)

LCI does not fit to impact factor?

+ heating system/fuel

Temperature

everything is construction (what do you mean here?)

specification (single, double, triple layer)

TBD, To do Partial implement

Unclear

LCA

or modify

enter 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 ~~found in our case study~~. The material data provided by John contains the materials used and ~~its~~ their thickness, especially for these components of the building: Façade, Inner walls ~~covering and construction~~, floor ~~covering and construction~~, and ceiling ~~and roof covering~~. The material data is needed for the calculation of the embodied impacts and to estimate U-Values, as input to the energy demand model.

I think here the data is the LCI data as the emissions are the results

GHG emissions

Environmental impact data: This data mainly comprises ~~of~~ the life cycle i~~nventory (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 operation~~s~~). 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~~ of the heating system ~~energy source found in the buildings~~.

as background database

specific data on

TBD

operational GHG emissions

Partial implement Merged

Validation Data: This data includes the measured ~~annual heat demands of the building, the thermal resistance of the building components (U-values), and the total greenhouse gas emissions of the building (IPCC GWP-100a, kg CO2 eq)~~. In this paper, we use the heat demand (operational emissions) and the ~~LCA~~ impacts (embodied emissions) from John's data for validation, which helps in finally evaluating the model developed here ~~and also the estimates from Buffat's model~~. Done

measured Done U-values, GHG Done

[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/

Added it in the end here, because this data helps in calculating the final impacts, instead of other way around

First motivate choice of GHG as impact category considered and reference source here (IPCC)

please be careful with terminology

usually people well know 'their' building → only for John the location needed to be found

TBD

2.2. Data Processing

move to SI

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 Section SI XX) 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 XX.
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 ??).
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.

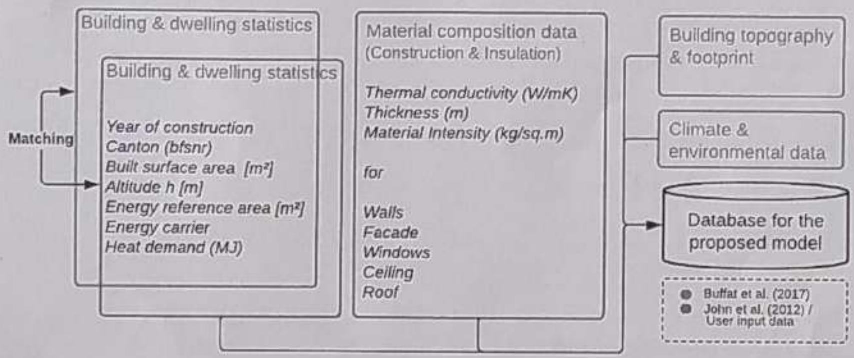


Figure 2: Data parameters and datasets used in the current model

→ just mention here that a matching algorithm was used to locate the buildings from John (→ Ref to SI), but that for normal users it would not be nec

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~~ Together with 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).

Do we not need an intro?

?

Operational

2.3.1. User Input

Edited

overwrite the default data of

The model developed here allows users to input ~~the data for one or many 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 following steps ~~and the Figure 3~~ shows an example of the input tool ?? information. ? What do you mean by "tool"?

1. List the building details

Interface? Done

What do you mean with "list"? Done

Done

Sorry! I get lost here → what does this describe?

- List the building basic properties ? which are?
- List the building components how?
- List the component material composition and details which?
- List the U Values of the materials if known

2. Create the material database for each component, allocate it to their thickness and U Values (lookup the U values if they are not provided from the database created) ?
3. Create the building database with their components listed
4. Add each new building to this database and calculate default values for thermal conductivity (U Values) based on the building typologies (construction, renovation year, location of the building, etc.)

1. Input of data

Done

S!

```
In [1]: # Build an input file for a building based on user input
        input_building = input('Does the user want to add a new building? (Y/N)')
        if input_building =='Y':

            #general information on the building
            input_year = int(input('What is the construction year of the building? '))

            #building components and their properties
            all_building_components = ('exterior wall','window','floor','basement')
            list_all_components = []
            for building_component in all_building_components:
                input_building_component = int(input('How many '+ building_component +' are there? [INT VALUES ONLY]')) #
                list_building_component = [building_component+"_"+ str(i+1) for i in range(input_building_component)] #e.
                list_all_components=list_all_components+list_building_component

            properties = ('Area(m2)','Given U-Value(W/mK)')
            dict_properties={}
            dict_properties_all ={}
            dict_materials ={}
            dict_materials_all={}

            for component in list_all_components:
                print('\n',component)
                for property_component in properties:
                    input_component = input('What is '+property_component+' of '+component+ '?')#e.g. area of wall 1: 100
                    dict_properties[property_component] = input_component
                dict_properties_all[component] = dict_properties
                dict_properties={}

                input_materials=int(input('How many materials are there in '+ component +'? [INT VALUES ONLY]'))
                for m in list(range(input_materials)):
                    input_material = input('What is the name of the material_'+str(m+1)+'?')
                    input_thickness = input('What is the thickness(m) of the material_'+str(m+1)+'?')
                    dict_materials[input_material]=input_thickness
                dict_materials_all[component]=dict_materials
                dict_materials={}


#           print('\n')
#           print('All components: ',list_all_components) #e.g. (wall1,wall2,floor1..)
#           print('All properties of components: ',dict_properties_all)
#           print('All materials of components: ',dict_materials_all)

Does the user want to add a new building? (Y/N)Y
What is the construction year of the building? 2000
How many exterior wall are there? [INT VALUES ONLY]1
How many window are there? [INT VALUES ONLY]1
How many floor are there? [INT VALUES ONLY]1
How many basement are there? [INT VALUES ONLY]2

 exterior wall_1
What is Area(m2) of exterior wall_1?100
What is Given U-Value(W/mK) of exterior wall_1?.9
How many materials are there in exterior wall_1? [INT VALUES ONLY]1
What is the name of the material_1?S
```

↳ consultation re John values

Suggest to make Table with an example entries

Figure 3: Example of user input

Question	Default	U1	U2

TBD -
Added one table with example entries..

U values and the associated components allocated in ~~Buffat's model~~ (Ref)

Notation in 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

Ref

2.3.2. Heating demand

Table 2 shows all the U values which are updated for each building in this model. These values are estimated in the original Buffat's model based on the construction and renovation years of the building (Section SI XX) 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 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 median U values for that component of the building (an example for this is shocased in Section SI XX).

TBD

Why median? If one wall has a huge U-value, the median does not include that (but all the heat will vanish through this wall) → average? surface weighted average would even be better

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

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

Not clear

For ~~estimating~~ quantifying 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.~~ model the heat demand as a function of ~~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.~~ (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. section 5 on heat demand as described in Buffat et al ( )

2.3.3. LCA

more to env. data calc

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~~ (Ref) to calculate~~s~~ the greenhouse gas emissions (kg CO_2 eq.) for the buildings. ~~We use the brightway tool 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.~~ operational GHG emissions. These calculations were done in Brightway

The enviro data is on background inventory data
Not sure if this fits there
check the edits

Or GHG score? This would not be LCI!

2.3.4. Scenarios

As ~~the~~ renovations may 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,

GHG

→ While here we only calculate GHG emissions, the tool could also be used to quantify other env. indicators.

How did you "connect" Brightway and the building model?

Explanation in SI, where the whole code is explained in steps. Should we discuss this in the main text too?

do you mean building footprint?

Table 3
Basic information on 12 Swiss buildings used in this model (as case study to showcase model results)

Done

include heating system column

insert scenarios as column indicating the changes for each building

	Canton	Construction Year	Accommodation units	Built surface area [m²]	Altitude h [m]	Energy standard
mfh01	Zurich	2012 (8022)	111	2350	402.7	MINERGIE
mfh02	Schwyz	2011 (8022)	2	190.2	606	MINERGIE-ECO
mfh03	Bern	2011 (8022)	3	163.4	593.33	MINERGIE-P
mfh04	Zurich	2010 (8021)	4	240	411.49	SIA 380
mfh05	Zurich	2007 (8021)	132	2218	457.75	MINERGIE-P-ECO
mfh06	Bern	2006 (8021)	3	777	500	MINERGIE-P-ECO
mfh07	Zurich	2011 (8022)	89	1810	418.1	MINERGIE
mfh08	Lucerne	2011 (8022)	6	375.3	498	MINERGIE-P-ECO
mfh09	St Gallen	2008 (8021)	4	135.15	805	MINERGIE-P-ECO
mfh10	Zurich	2012 (8022)	10	411	440	MINERGIE
mfh11	Bern	2012 (8022)	22	665	565	MINERGIE-P-ECO
mfh12	Lucerne	2008 (8021)	10	168.75	556	

Done

→ provide Reference for these labels as footnote to the table

delete or specify that this is not the building hight

Done

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.

maybe

- "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 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):

it is just one option you could also replace insulation

don't see this in Table 3

  1. Standard refurbishment~~: to~~ transition the resulting U-value of the refurbished building components between the legal minimum (EnDK 2008) (cite) and the MINERGIE standard (cite) which means the U Values for walls < 0.15 W/(m^{2}K), for windows < 1 W/(m^{2}K) (cite).
  2. Efficiency refurbishment: to transition towards a passive-house or MINERGIE-P (cite) 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) (cite)

- 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. ~~Final note,~~ (2) Also the users of the tool 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.

Done

Paragraph

Done

(1) Note that these scenarios are performed for illustrating the capabilities of the tool developed here. All buildings ~~from~~ in Table 3 are relatively new and well insulated and in reality they would probably not (yet) be candidates for 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 3 below (detailed in Table SI XX).

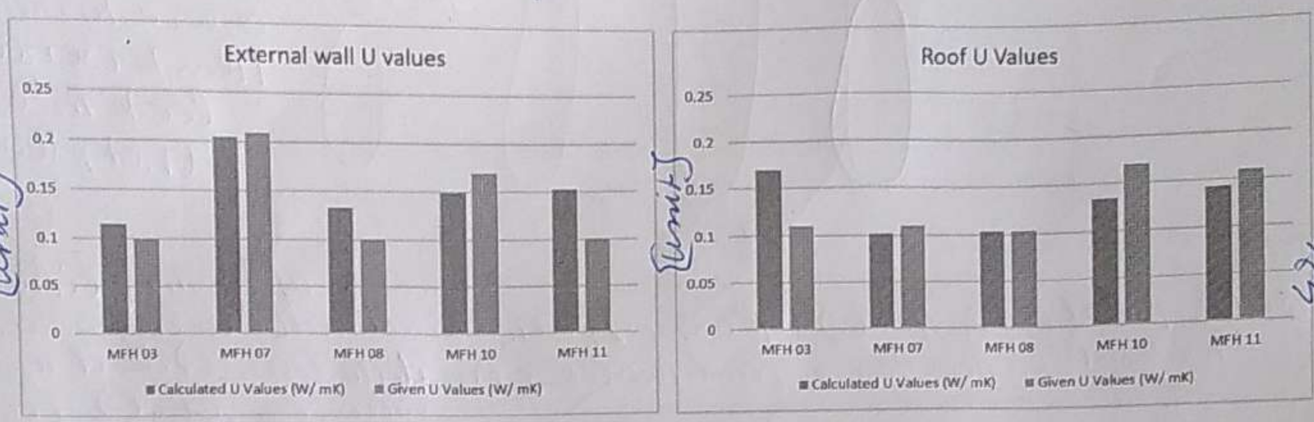
measured were these measured or also calculated?

3.1. U values

Reported Done Done

In this section, we ~~will~~ present how the U values calculated in our model vary compared to the ~~measured~~ reported U values for the 12 swiss buildings. The following Figure 4 shows an example with the calculated (in our model) and ~~measured~~ 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 ~~help in correctly estimating the final heat demand~~ confirms the reliability of the U-values calculation implemented in the tool. Done In the Section SI XX we also show these U values for all the building components for all the buildings, compared to the ~~measured~~ reported U Values and the ~~existing~~ U Values ~~which are probabilistically~~ estimated for these buildings by the Buffat et al. (2017) model.

insert y-axis label [unit]



just a very clumsy chart then.. but can add two of them one after another.

Figure 4: Results of U Values: calculated (in our model) vs ~~measured~~ reported by John ( ) for 5 buildings (see Table 3)

Done

3.2. Heating demand

simplified estimation approach of Buffat et al.

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 5 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 ~~old~~ U values). As Done shown further in the Table 4, ~~it is clear that~~ the current model shows a very high improvement in the final heat demand given the factors compared to the ~~old model with probabilistic~~ previous simplified U values. The buildings with highest improvement in relative error (mfh 03, 06 and 08) are also those where the U Values changed ~~significantly~~ most due to ~~the change in material~~ new specification of composition. Also note that these are the buildings with some of the highest estimated heating demand (due to the probabilistic allocation ? removed of u values instead of more accurate ones based on the material compositions). This provides a scope for our model to correct the "default" u values for these building typologies, ~~correcting~~ improving the estimations of ~~new~~ buildings' energy demands. Note that ~~though~~ the relative error reduces with the new model, the high error for some of the buildings (compared to the measured values) exist due to multiple reasons including the user behavior, etc. which is not included in the model currently (discussed more in Section 4) Added but want to check the rationale behind this and the fact that the measured data refer 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 Section SI XX. ~~This impact is~~ added to the total space heating demand estimated in the above Section 3.2 above) ~~giving the Life Cycle Assessment of the building. The~~ Figure 6 shows the Greenhouse Gas (GHG) emissions calculated annually per square meter 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 m2/ accommodation unit and 259 m2/unit, respectively). Sorry, cant read this m²/m²? should be unit?

These embodied GHG are ... operational GHG (calculated based ... heating specific GHG and the ...

Done

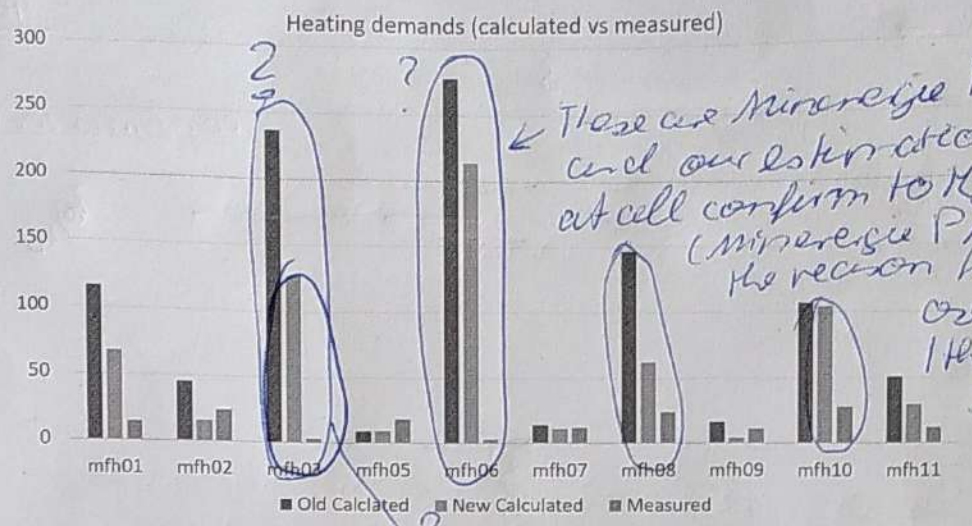
3.4. Scenarios

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

It is just something provided by the architects, so it is not really mentioned how and when it is measured

(*) Rhythima, please check if this was the case. How was the John heat data measured and what was the measuring period?

TBD



These are Minergie P buildings and our estimations do not at all confirm to the standard (minergie P). Do we know the reason for this vast overestimation? I think we need to look into this (not plausible)

Done

Figure 5: Heat demand estimation ~~and measured data~~ of the simplified (old) approach by Buffat ( ) (left colums), the updated model using accurate material specifications of each building (middle colums) and reported values by John ( ) (right colums)

Table 4
Relative errors for the models in estimation of space heat demand

how calculated?

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**

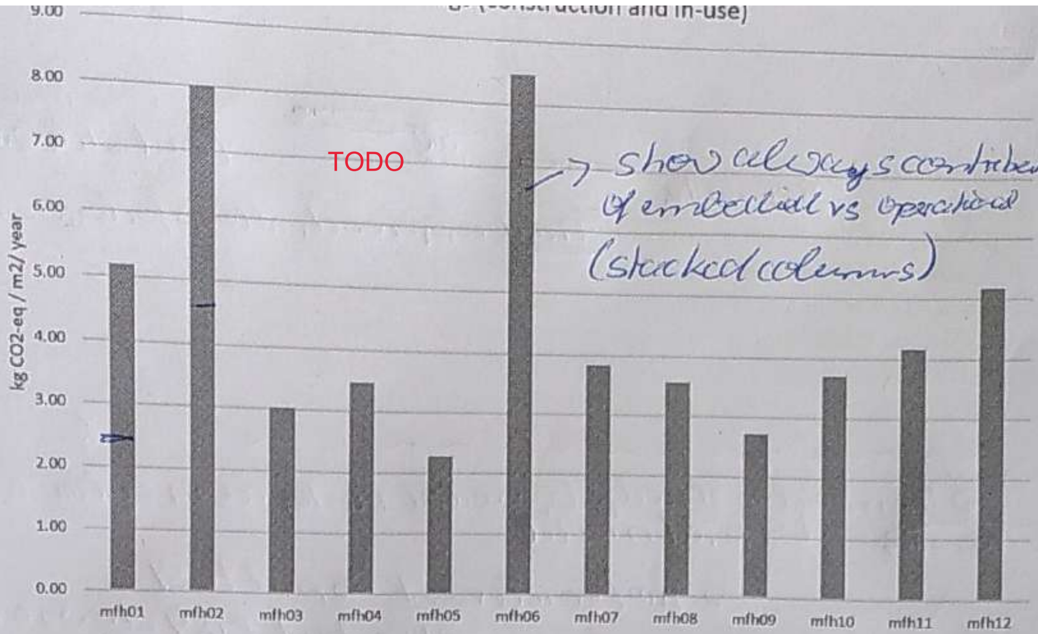
how does this fit to the overestimation by more than a factor of 10?

these errors are relative to the old value, and not the measure value

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 5.

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 in Figure 7, 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 7 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).



TODO

→ show always contribution of embodied vs operational (stacked columns)

☐ embodied GHG

▨ operational GHG

Figure 6: LCA (Greenhouse gas emissions) for all the buildings split by embodied and operational GHG. The lifetime ~~of~~ assumed for all buildings was X years.

Done

Table 5
Changes in building parameters introduced as per the scenarios

?

avoid abbreviation (make it understandable to the reader)

	Scenario 1: Insulation				Scenario 2: Heating	
	U_We_old	U_We_new	material	+MI_new (kg/m2a)	Base source	New 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

✓

Done

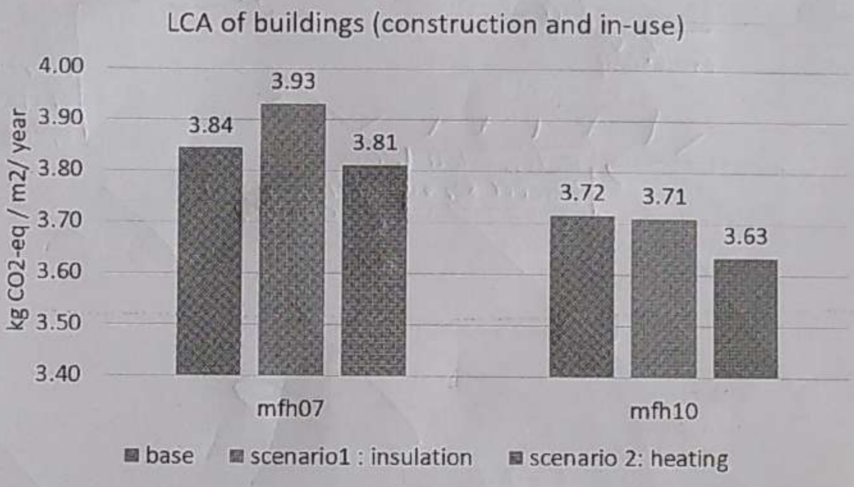


Figure 7: Scenario results: LCA (GHG) for all the buildings (see Tab 5 for scenarios)

only 2 ?

Done

operational GHG emis... rather low

Done

4. Discussion and Outlook

Takeaways and highlights from the model :

not model

> Considering the results, for the case of the 12 buildings (new energy-efficient buildings, only around 10 years old), the embodied emissions clearly show to have a significant impact ~~in the scenarios~~. → base case

Example of minergieP

> The method improved the energy estimations ~~significantly~~ for ~~most~~ all of the buildings (but still greatly deviating from real values)

Done

> The method proposed here ~~also showcased~~ presents an improved way of calculating the LCA for the buildings, with the possibility for integrating data provided by users. Tired approach allows for large-scale modelling while allowing for detailed assessment if data available

approaches like

> We can also integrate data from other research in different regions, e.g. an extension of our study can allow integration of 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 Trigaux, Allacker and Debacker (2021) ?

Done

> We also propose a framework to upscale the model by better estimation of U Values (even with missing material data) (Figure 8) → The model is already upscaled (integrate in earlier sections) ↳ tired model

Results: also scenarios

Limitations and improvements of the model :

> Uncertainties in matching building → not so relevant → put to SI

Done

> Uncertainties in thermal conductivity for similar materials → yes, but Fig 4 shows a rather good match

> Electricity mix 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 → needs to be mentioned earlier → above you say 30 minutes

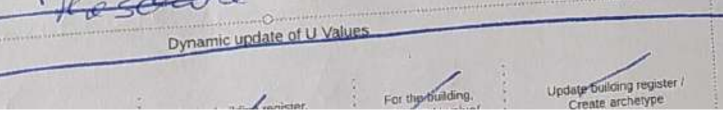
NOt clear

> User behavior is not included, even though heating consumption estimations from Froemelt, Buffat and Hellweg (2020) are included.

??? Done

Resource or hot water altogether?

or consumption?



5. Conclusion

> ~~Buildings are high emitters, in their construction, maintenance and renovation phase.~~ →introduction
~~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 →here a model that allows combined ces
> Our model creates a tool 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 → these renovations are hypothetical and not realistic
> There is a possibility to improve this model further with better data sources from electricity and heating water sources, and user behavior.
> XX
> XX
> XX
> XX
>XX

tbd
here we need to be careful in the interpretation

Acknowledgement

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Tiered approach (instead of Fig 8)
↳ include in <u>Methods</u> section

① for all components: ~~...~~

material composition known?

yes → calculate specific U-value of the component

no ↓

Use simplified archetype approach of Buffat ( ) to estimate U-value (based on renovation/construction year)

② Calculate energy demand as a function of U-values (1), ~~clim~~ climate (solar radiation, temperature), shading, building geometry etc. following Buffat

③ Calculate embodied + operational GHG
(material amount and background LCA data) (heat demand and background LCA data)

④ Calculate scenarios of building heating source modifications