Supplementary Materials

Towards Urban Mining – Estimating the potential environmental benefits by applying an alternative construction practice. A case study from Switzerland.

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1. Residential building types in Switzerland.

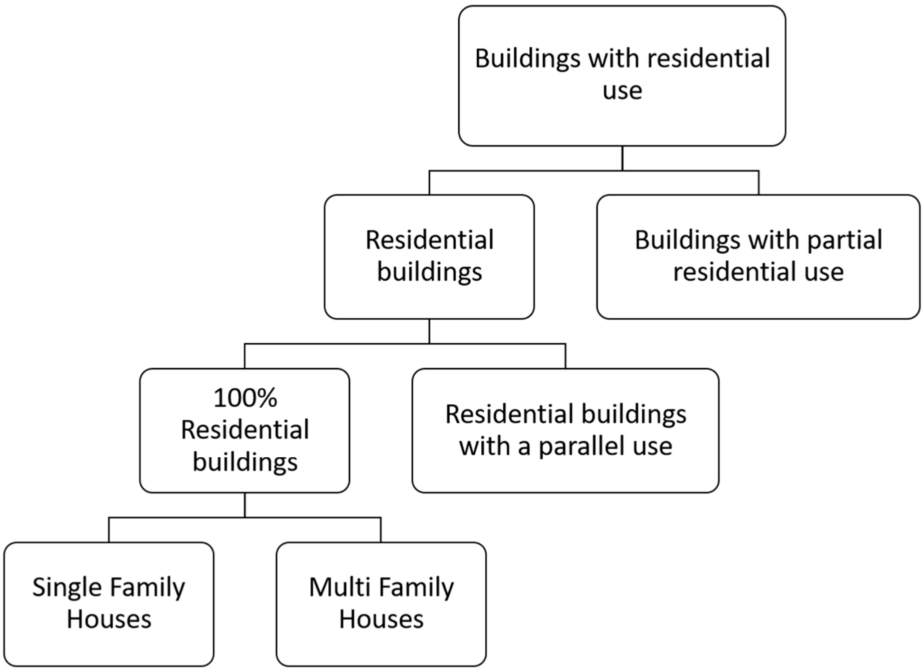

Figure S1. Types of buildings in Switzerland (Bundesamt für Statistik, 2017).

2. Life Cycle Inventory (LCI).

This section provides foreground data about material, transport, construction, energy and demolition waste (CDW) calculation of all buildings considered for the study and reports the key assumptions behind these calculations. The densities included in the following tables were taken from the KBOB list (KBOB, 2014), which includes life cycle assessment data on a variety of building materials. The density of the mushroom panels are the exception to this case, as it was not included on the list due to the fact that is a novel material. Hence, its density derives from the company Evocative design.

2.1. Material calculation (A1-A3)

As a simplification, only materials that are essential for the construction of the backbone of the different default buildings are introduced into the analysis (summarized in tables Table S1 and

Table **S2**). As reported in the main text, aspects such as mechanical and electrical equipment or (inside/outside) paints are not taken into consideration for this study here, because most of them could be assumed to be similar in all cases. Doors, window frames and stairs are excluded from the study, based on the Swiss Standards for the calculation of the grey energy of buildings, i.e. the SIA 2032 standard (SIA, 2010). Further suggestions reported in this standard (such as the calculation of external walls without a deduction for the windows, or the calculation of internal walls without a deduction for the doors) are not taken into account. Materials for foundation have not been taken into consideration due to the variety of buildings and – as a result – variety of foundation options that would be required between the lightweight SFH and heavyweight SFH.

Table S1. Material quantity calculation for the circular modeled buildings.

Materials	Density (kg/m³)	Volume (m³)					
		1-floor SFH			2-floor SFH	3-floor SFH	3-floor MFH
		ESR = 1	ESR = 1.5	ESR = 2.5	ESR = 1.5	ESR = 1.5	ESR = 1.5
Wooden fassade	600	3.32	3.40	3.68	4.62	5.46	11.75
Wooden formwork	600	17.57	18.00	18.34	27.37	29.66	84.82
Wooden beams	600	15.44	15.97	15.44	12.67	22.35	31.24
Stonewool insulation	100	86.89	88.01	89.28	79.78	78.78	273.43
Vapor barrier	920	0.09	0.09	0.09	0.09	0.09	0.25
Straw mushroom panels	122	6.52	7.98	8.11	6.35	10.46	40.36
Ceiling boards	600	9.60	9.60	9.60	14.40	16.00	60.00
Wooden floor	600	3.00	3.00	3.00	1.50	1.00	3.75
Cooper roof	8900	0.07	0.07	0.07	0.03	0.02	0.08
Double glazing	2573	0.24	0.24	0.27	0.48	0.72	0.72
UV foil	1700	0.02	0.02	0.02	0.02	0.03	0.06

Table S2. Material quantity calculation for the conventional modeled SFH (ESR = 1.5).

Materials	Density (kg/m³)	Volume (m³)		
		1-floor	2-floor	3-floor
Wooden protective layer	600	3.27	4.44	5.25
Concrete	2420	69.12	63.60	63.56
Wooden supporting beams (30X60 mm)	600	0.24	0.34	0.41
EPS	30	85.10	79.25	80.75
Vapor barrier	920	0.02	0.02	0.02
Gypsum fiberboard	850	1.12	1.26	1.42
Bricks	1845	11.15	12.57	14.16
Stucco	1500	1.07	1.21	1.36
Cover plaster	1200	0.89	1.01	1.13
Wooden formwork	600	0.00	1.50	2.00
Cement plaster	1850	9.60	4.80	3.20
Aggregates	2000	6.00	3.00	2.00

Bitumen	1100	1.44	0.72	0.48
Reinforcing steel	7850	0.69	0.64	0.64
Double glazing	2573	0.24	0.48	0.72

2.2. *Transport (A4, C2)*

For the transport of materials (see Table S3 and Table S4) from the production companies to the building site and from the building site to treatment facilities, trucks were considered, with a covered distance of 100 km.

Table S3. Transport estimation for circular building materials.

Materials	Density (kg/m³)	Transport (tkm)					
		1-floor SFH			2-floor SFH	3-floor SFH	3-floor MFH
		ESR = 1	ESR = 1.5	ESR = 2.5	ESR = 1.5	ESR = 1.5	ESR = 1.5
Wooden fassade	600	199.4	204.1	220.7	277.2	327.8	705.1
Wooden formwork	600	1054.2	1080.1	1100.1	1642.0	1779.6	5089.2
Wooden beams	600	926.2	958.3	926.2	760.0	1340.7	1874.5
Stonewool insulation	100	868.9	880.1	892.8	797.8	787.8	2734.3
Vapor barrier	920	8.5	8.6	8.7	8.1	8.1	23.2
Straw mushroom panels	122	79.6	97.3	98.9	77.4	127.7	492.3
Wooden roof boards	600	576.0	576.0	576.0	864.0	960.0	3600.0
Wooden floor	600	180.0	180.0	180.0	90.0	60.0	225.0
Cooper roof	8900	59.7	59.7	59.7	29.8	19.9	74.6
Double glazing	2573	61.4	61.4	69.4	122.8	184.2	185.3
UV foil	1700	2.7	2.8	3.0	3.8	4.5	9.6
Total transport to building site		4016.5	4108.3	4135.5	4672.8	5600.2	15013.1

Table S4. Transport estimation for the conventional buildings with ESR = 1.5.

Materials	Density (kg/m³)	Transport (tkm)		
		1-floor	2-floor	3-floor
Wooden protective layer	600	195.9	266.1	314.9
Concrete	2420	16725.9	15391.4	15380.6
Wooden beams (30X60 mm)	600	14.2	20.2	24.8
EPS	30	255.3	237.8	242.2
Vapor barrier	920	2.2	2.2	2.2
Gypsum fiberboard	850	94.8	106.8	120.4
Bricks	1845	2057.2	2318.7	2612.8
Stucco	1500	160.6	181.0	203.9
Cover plaster	1200	107.0	120.6	135.9
Wooden formwork	600	0.0	90.0	120.0
Cement plaster	1850	1776.0	888.0	592.0

Aggregates	2000	1200.0	600.0	400.0
Bitumen	1100	158.4	79.2	52.8
Reinforcing steel	7850	542.6	499.3	498.9
Double glazing	2573	61.4	122.8	184.2
Total transport to building site		23351.4	20924.0	20885.6

2.3. *Construction & Deconstruction (A5, C1)*

The design-for-disassembly concept not only allows for easier construction and deconstruction of the buildings, which leads subsequently to lower environmental impact during those stages but also allows for minimum loss of materials during those stages and as a result maximum recovery of those materials that can either be utilized. Hence, it minimizes the usage of building equipment and time for the installation process. The assumptions for the construction and installation of building elements are shown in Table S5. Prefabrication of elements for this study has not been considered due to lack of data. For the deconstruction phase, concrete mixer is replaced by an excavation skid-steel loader but in principle remains the same. Preparatory works for foundation are not taken into account.

Table S5. Construction equipment for wooden and concrete buildings.

Circular (wooden) buildings			
SFH		MFH	
Operation (hr)	Machinery	Operation (hr)	Machinery
15	Crane Drills (500 W)	20	Crane Drills (500 W)
Conventional (concrete) SFH buildings			
Operation (hr)		Machinery	
10		Concrete mixer Drills (500 W)	

2.4. *Material replacement (B4)*

The replacement stage gains significant value, especially when an appropriate Design-for-Disassembly concept is placed at the center of the design, early from the planning phase of the building. Apart from the time and construction flexibility it provides, it gives the opportunity to easily replace any defect building element even during operation of the said building, avoiding that way a repair of an element or even a total refurbishment of the building, if needed. Therefore, replacement is considered for both concrete and wooden buildings and conforms to again to the Swiss standard for grey energy of buildings (SIA, 2010). Table S6 again provides an overview of the replaced materials. All principal activities connected with material replacement such as production of the new element, transport and integration to building site, treatment of the element. Reuse potential is included in module D.

Table S6. Replaced elements considered for circular and conventional buildings.

Replacing elements	Element lifetime	Replacement magnitude
Window glazing	30	1
UV foil	30	1
Outside fassade	40	1

2.5. Energy consumption of buildings (B6)

Table S7 exhibits the annual electricity and thermal energy required by the circular and conventional buildings. The detailed estimation of the modeled buildings' energy consumption is out of the scope of this study. The energy demand of each building is assessed through the use of SIA 2024 building tool, which conforms to SIA 2024 standard (SIA, 2015), which provides reference values for all aspects of building-related energy consumption. The provided standard values were used for an average calculation of each building's energy demand. The electricity country mix of Switzerland provided within the Ecoinvent database v3.4 ("Ecoinvent Data v3.4-Recycled-Content System Model," 2017) is considered for domestic use, while the (underfloor) heating and domestic hot water demand was covered through the use of heat pump.

Table S7. Annual energy consumption per gross floor area of the model buildings according to SIA 2024 building tool.

Building type	Total electricity (kWh_e / m^2)			Total thermal energy (kWh_{th} / m^2)		
	Appliances	Lighting	Ventilation	Cooling	Heating	Domestic hot water
SFH	14.2	4.0	1.0	0.0	28.8	13.5
MFH	13.8	4.5	1.7	0.0	19.0	19.2

2.6. End-of-life stage (C2-4)

The end-of-life stage of a building commences with its demolition (conventional buildings) or deconstruction (circular buildings) and ends with the treatment of its individual materials or disposal of its small fraction that cannot be treated. Transport of the CDW to the treatment facilities follows the same patterns as in stage A4.

Table S8 and Table S9 show the calculated construction and demolition waste (CDW), along with the chosen treatment option for the circular and conventional buildings respectively. In this study, losses stemming from the demolition of concrete buildings are not taken into account. For the circular buildings, after deconstruction the materials are collected back and stored until they are reused in the construction sector, meaning that no treatment is considered for them. CDW from the conventional buildings are mostly processed in a sorting facility and some of the collected materials receive no treatment at all as in the circular buildings and they remain stored until reused directly in another project. No direct landfilling of primary CDW is taking place in this study.

Table S8. Generated CDW of circular buildings.

Materials	Weight (tons)						Treatment	Post treatment use
	1-floor SFH			2-floor SFH	3-floor SFH	3-floor MFH		
	ESR = 1	ESR = 1.5	ESR = 2.5	ESR = 1.5	ESR = 1.5	ESR = 1.5		
Wooden fassade	1.99	2.04	2.21	2.77	3.28	7.05	No treatment considered	Reuse
Wooden formwork	10.54	10.80	11.00	16.42	17.80	50.89		
Wooden beams	9.26	9.58	9.26	7.60	13.41	18.75		
Stonewool insulation	8.69	8.80	8.93	7.98	7.88	27.34		
Vapor barrier	0.09	0.09	0.09	0.08	0.08	0.23		
Straw mushroom panels	0.80	0.97	0.99	0.77	1.28	4.92		
Ceiling boards	5.76	5.76	5.76	8.64	9.60	36.00		
Wooden floor	1.80	1.80	1.80	0.90	0.60	2.25		
Cooper roof	0.60	0.60	0.60	0.30	0.20	0.75		
Double glazing	0.61	0.61	0.69	1.23	1.84	1.85		
UV foil	0.03	0.03	0.03	0.04	0.04	0.10		
Total	40.17	41.08	41.36	46.73	56.00	150.13	-	-

Table S9. Generated CDW of conventional buildings.

Materials	Weight (tons)			Treatment	Post treatment use
	1-floor	2-floor	3-floor		
Wooden protective layer	1.96	2.66	3.15	-	Reuse
Concrete	167.26	153.91	153.81	Sorting plant	Sand & limestone
Wooden beams (30X60 mm)	0.14	0.20	0.25	-	Reuse
EPS	2.55	2.38	2.42	-	Reuse
Vapor barrier	0.02	0.02	0.02	-	Reuse

Gypsum fiberboard	0.95	1.07	1.20	Sorting plant	gypsum recovery
Bricks	20.57	23.19	26.13	Sorting plant	Sand & limestone
Stucco	1.61	1.81	2.04	Sorting plant	Sand & limestone
Cover plaster	1.07	1.21	1.36	Sorting plant	-
Wooden formwork	0.00	0.90	1.20	-	Reuse
Cement	17.76	8.88	5.92	Sorting plant	Reuse
Aggregates	12.00	6.00	4.00	-	Reuse
Bitumen	1.58	0.79	0.53	Incineration	-
Reinforcing steel	5.43	4.99	4.99	recycling	Reuse
Double glazing	0.61	1.23	1.84	recycling	Reuse
Total	233.51	209.24	208.86	-	-

2.7. *Reuse / recovery potential (D)*

This stage of the LCA reports the avoided environmental impact resulting from recycling and/or reuse of materials after building demolition. More specifically, the extracted fractions from the end-of-life treatment of the materials – not going to landfill - serve as inputs to this stage and the net (negative) impact originates from avoiding production of the original material for the specified use outside of the system boundaries (e.g another construction). Table S8 and Table S9 illustrates in a summarized form the specified (post-treatment) use of materials in other projects for circular and conventional buildings.

Pertaining to the concrete buildings, inert materials are crushed in sorting facilities in order to recover sand (70%) and limestone (30%). Direct reuse is hypothesized only for the wooden protective layer, vapor barrier, aggregates from the roof and the recycled reinforced steel. Energy recovery from incineration of materials is not considered in this study, as the focus is strictly on the material side.

3. Results

Table S10. Life-cycle impacts of the model buildings per each indicator (CED, GWP and EC) and life-cycle stage.

Indicator	CED - Cumulative Energy Demand (MJ-eq / (m²×a))								
Geometry & type of building	Conventional			Circular					
	SFH 1 - 1.5	SFH 2 - 1.5	SFH 3 - 1.5	SFH 1 - 1	SFH 1 - 1.5	SFH 1 - 2.5	SFH 2 - 1.5	SFH 3 - 1.5	MFH 3 - 1.5
Production (A1-3)	77.84	72.26	71.96	52.16	52.91	53.63	61.76	68.11	54.75
Transport (A4)	26.24	23.51	23.47	4.51	4.62	4.65	5.25	6.29	4.50
Construction (A5)	0.41	0.41	0.41	0.21	0.21	0.21	0.21	0.21	0.09
Replacement (B4)	2.59	4.22	5.68	3.27	3.32	3.67	5.17	6.78	2.93
Energy consumption (B6)	243.64	243.64	243.64	243.64	243.64	243.64	243.64	243.64	242.50
Deconstruction (C1)	0.14	0.14	0.14	0.01	0.01	0.01	0.01	0.01	0.00
Transport (C2)	26.24	23.51	23.47	4.51	4.62	4.65	5.25	6.29	4.50
Treatment (C3)	2.43	2.15	2.12	0.00	0.00	0.00	0.00	0.00	0.00
Reuse potential (D)	-54.33	-53.17	-55.40	-52.16	-52.91	-53.63	-61.76	-68.11	-54.75
Total	379.54	369.85	370.90	308.31	309.33	310.46	321.29	331.33	309.27
Indicator	GWP - Global Warming Potential (kg CO_2-Eq / (m²×a))								
Geometry & type of building	Concrete			Wooden					
	SFH 1 - 1.5	SFH 2 - 1.5	SFH 3 - 1.5	SFH 1 - 1	SFH 1 - 1.5	SFH 1 - 2.5	SFH 2 - 1.5	SFH 3 - 1.5	MFH 3 - 1.5
Production (A1-3)	5.48	5.31	5.31	3.62	3.68	3.76	4.26	4.77	3.62
Transport (A4)	1.68	1.51	1.50	0.29	0.30	0.30	0.34	0.40	0.29
Construction (A5)	0.03	0.03	0.03	0.01	0.01	0.01	0.01	0.01	0.01
Replacement (B4)	0.20	0.32	0.44	0.68	0.69	0.76	1.00	1.23	0.63
Energy consumption (B6)	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.61
Deconstruction (C1)	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Transport (C2)	1.68	1.51	1.50	0.29	0.30	0.30	0.34	0.40	0.29
Treatment (C3)	0.63	0.36	0.27	0.00	0.00	0.00	0.00	0.00	0.00
Reuse potential (D)	-3.14	-3.09	-3.23	-3.62	-3.68	-3.76	-4.26	-4.77	-3.62
Total	15.18	14.51	14.54	10.36	10.45	10.61	11.42	12.29	10.44
Indicator	EC - Ecological Scarcity (Eco-points/(m²×a))								
Geometry & type of building	Concrete			Wooden					
	SFH 1 - 1.5	SFH 2 - 1.5	SFH 3 - 1.5	SFH 1 - 1	SFH 1 - 1.5	SFH 1 - 2.5	SFH 2 - 1.5	SFH 3 - 1.5	MFH 3 - 1.5
Production (A1-3)	7229	7021	7052	5868	5966	6058	6806	7698	5931
Transport (A4)	1737	1556	1553	299	306	308	348	417	298
Construction (A5)	29	29	29	15	15	15	15	15	6
Replacement (B4)	298	468	625	899	918	1001	1307	1605	829
Energy consumption (B6)	10165	10165	10165	10165	10165	10165	10165	10165	10230
Deconstruction (C1)	10	10	10	0	0	0	0	0	0
Transport (C2)	1737	1556	1553	299	306	308	348	417	298
Treatment (C3)	738	565	523	0	0	0	0	0	0
Reuse potential (D)	-4897	-4774	-4957	-5868	-5966	-6058	-6806	-7698	-5931
Total	21943	21370	21510	17546	17677	17856	18990	20318	17593

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