Towards Urban Mining—Estimating the Potential Environmental Benefits by Applying an Alternative Construction Practice. A Case Study from Switzerland

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Abstract: Modern cities emerged as the main accumulator for primary and waste materials. Recovery of both types from buildings after demolition/disassembly creates a secondary material stream that could relieve pressure from primary resources. Urban mining represents this circular approach, and its application depends on redefining current construction practice. Through the life cycle assessment (LCA) methodology and assuming primary resources as step zero of urban mining, this study estimates the impacts and benefits of conventional versus a circular construction practice applied to various buildings with different parameters and the country-level environmental potential savings that could be achieved through this switch in construction practice—using the increase of the residential building stock in Switzerland between 2012 and 2016 as a case study and key values from the experimental unit "Urban Mining and Recycling", designed by Werner Sobek with Dirk E. Hebel and Felix Heisel and installed inside the NEST (Next Evolution in Sustainable Building Technologies) research building on the Empa campus in Switzerland. The results exhibit lower total impacts (at least 16% in each examined impact category) at building level and resulting benefits (i.e., 68–117 kt CO_2-Eq) at country level over five years, which can be further reduced/increased respectively by using existing or recycled components, instead of virgin materials.

Keywords: urban mining; life cycle assessment; sustainability; circular economy; building sector

1. Introduction

On a global scale, cities are one of the main contributors to (i) environmental pollution (accounting for approximately 80% of global carbon emissions), (ii) energy consumption (500 EJ of primary energy, representing a share of 67 to 76% of the global energy supply), and (iii) to the primary material demand (60–80% of global consumption) [1,2]. Buildings—as an integral part of cities—account for more than a third of the world's resource consumption in construction, 40% of global energy consumption (including embodied energy), 12% of fresh water use, and generate at the same time 40% of global greenhouse gas (GHG) emissions and are responsible for 40% of the waste going to landfill [3] (p. 144). In the light of all these environmental issues, the construction industry needs to take action and make a swift turn towards a more sustainable use of its resources.

One resource-centric approach that could displace conventional practices in the construction sector is urban mining (UM). UM comprises the activities and processes of recovering materials and elements from used buildings, infrastructure, or waste [4], perceiving the building stock as a unified

system that serves as a material repository, and waste (irrespective of its source) as an intermediate state through which something new can emerge [5]. Such a circular approach represents a radical shift from the currently prevailing linear economic model (based on the take-make-use-dispose model of production) [6,7] that does not identify or consider waste as a potential resource [8], thus resulting often in inefficient utilization of material resources [9]. The term "urban mining" can be attributed to Jane Jacobs, expressing the idea in the 1960s that "cities are the mines of the future" [10]. The term was created due to rising environmental concerns regarding the recycling of waste, scraps, and garbage. Through recycling of various products, significant quantities of materials could be regained [11]. Jane Jacob's statement depended on some undisputed facts that are even more easily observable today than in the 1960s [12], e.g., that hard-rock mining is an environmentally troublesome and energy intensive process, that the metal content in the ores is continuously decreasing while extraction rates are simultaneously increasing, and that significant fractions of mined metals flow to cities and are used in buildings and the transportation sector. Since the 1980s, the concept has gained increasing support from various companies, regions, and countries [13]. As one result, an increase of municipal waste recycling along with the share of recycled materials used—related to the total material demand—has been reported in Europe from 2008 to 2016 [14]. However, the total potential of a circular economy is still not nearly exploited by that, considering that—on a European level—only 12% of the total demand of materials are covered by recycled materials [15], and that—on a global level—the world economy is only about 9% circular [16].

Seen from a material production perspective, the amount of accumulated materials in buildings can be compared with existing natural reserves [4]. Cities are at the point of becoming the mines of the future—playing both the role of the consumer and the supplier of (their own) resources. Urban mining will help cities to expand in more sustainable ways [17], by reducing the need for primary resources and by avoiding at the same time the environmental impacts associated with the production of such resources—as reuse and recycling processes typically require less energy input than virgin material production [18]. Circular materials use contributes to the mitigation of GHG emissions in the long run and thus to environmental protection [19]. In addition, the utilization of secondary resources (either directly or in a processed form) decreases not only the input required from primary resources but also the required space for landfilling of these materials at the end of the life-cycle [20]. Even by assuming that the impacts of the recycling process for a specific material are equal to the ones from its primary production pathway, the waste output in the former case will decrease, leading to less GHG emissions from disposal [21]. Therefore, UM contributes to environmental protection by introducing a circular flow of materials in the building sector.

In the past few years, several projects have been realized in creating buildings from recycled or reclaimed materials, such as the "Manifesto House" in Curacavi, Chile [22], the "Oikos" project at the London Festival of Architecture in 2010 [23], the "House of Waste" built from recycled materials at the University of Brighton [24], as well as the "Urban Mining and Recycling" (UMAR) unit designed by Werner Sobek with Dirk E. Hebel and Felix Heisel of the NEST building (NEST stands for Next Evolution in Sustainable Building Technologies and represents a modular research and innovation building of Empa and Eawag in Dübendorf, Switzerland, where new technologies, materials and energy systems for the future construction market can be tested, researched, honed, and validated under realistic conditions, making possible an acceleration of the whole innovation process for the building sector). The UMAR unit is constructed from separable, mono-material resources that are completely reusable, recyclable, or compostable. Placing life-cycle thinking at the forefront of the design, UMAR is designed both as a high-quality residence for today and as a material depot for future construction. The latter case is, however, so far, the only example where a "design-for-disassembly" concept has been integrated from the early planning stages on, allowing the complete reintegration of all materials into their respective true-type material cycles after the end of their use phase in the building. The latter case is, however, so far, the only example where a "design-for-disassembly" concept has been integrated from the early planning stages on, allowing the complete reintegration

of all materials into their respective true-type material cycles after the end of their use phase in the building. A detailed analysis of the material circularity in the UMAR unit has also been performed [25].

However, at the building level, all the potential environmental benefits of the UM concept may be realized only if (a) the concept is carefully integrated within a (broader) circular economy allowing for systematic reuse, recovery, recycling, or reprocessing of the different fractions originating from the building at the end of its use, and (b) if design-for-disassembly concepts are an integral element of design and construction [26], being a necessary requirement in order to achieve a maximum recovery rate of the various materials within the building. This implies that the prior implementation and integration of the two above-mentioned concepts into the building design—considered as precursor activities to UM—and consequently the commitment and adaptability of the entire construction industry comprise one prerequisite for the successful application of the UM concept and the transformation of the building stock into a future materials depot. At the city level, up to this point, the location of material recycling operations has not coincided with the location of the UM operations. Material treatment should be considered as a whole to maximize the UM potential, which means that material recovery and recycling facilities operating at a high level of energy efficiency need to be located in the proximity of, or even within, the urban surroundings in order to minimize transportation distances, therefore reducing the overall required energy for recycling and reprocessing [27].

To date, various studies have attempted to evaluate the potential and the merits of UM and its application. Aurora et al. have estimated the UM and reuse potential of various building components for the city of Singapore [28], and focused on the social, economic, and policy relevance of the UM strategy of India in another publication [19]. Angelis-Dimakis et al. assessed the urban iron mining potential for the city of Huddersfield [29]. In addition, Jones et al. have assessed not only the potential amount of secondary materials that could be recovered through enhanced landfill mining [30]—an integral part of UM [4]—but also the potential environmental CO_2 savings that could be achieved through such an approach.

However, to the best of the authors' knowledge, no study so far has assessed the potential environmental benefits stemming from a (theoretical) application of the UM concept in the building sector on a country scale. Since the UM concept is pursuant to the definitions of circular economy [4,31] and places life-cycle thinking at the core of design, the life cycle assessment (LCA) methodology is an ideal tool not only to quantify the related environmental impacts [32], but also to take into account the resulting benefits of such a new construction practice. The latter includes (i) a design-for-disassembly approach that ensures maximum material recovery and minimal disassembly effort, and (ii) materials that are meant to be recycled and/or reused after their end of life (henceforth called "circularity-oriented construction practice") compared to today's behavior (both design principles adopted from the UMAR unit [26]). With this intent in mind, the present study aims to assess the environmental impacts and benefits on a building level obtainable from the application of this circularity-oriented construction practice versus the conventional (linear) practice, and to estimate the resulting (theoretically maximum) environmental sustainability potential on a country level that could arise from a possible switch to such a circular construction practice. The study uses Switzerland as reference area and the case study of the UMAR unit [26,33] in the NEST building as a starting point, considering the first life-cycle of the construction materials (production from primary resources) as the initiation point for a (future) UM cycle. Thus, the manuscript at hand is structured in the following way: Section 2 explains the methodology applied by providing an overview of the changes in the Swiss residential building sector over recent years, describing the formation of the model residential buildings used in this study, and including all LCA-related elements and assumptions. Section 3 shows and discusses the results on both levels, i.e., the individual building level as well as the environmental potential for Switzerland, and Section 4 displays the limitations of this study and the further future work that needs to be conducted.

2. Materials and Methods

2.1. Applied Methodology

Figure 1 provides an overview of the stepwise procedure applied in order to assess the overall sustainability potential resulting from the application of the circularity-oriented construction approach in the area of residential buildings in Switzerland. In a first step (shown at the bottom of Figure 1), statistical data on the development of the Swiss residential building sector (i.e., type and number of buildings) have been collected from official statistics [34] for an estimation of the net change in the built environment (concerning residential buildings only) during the reference period of this study (i.e., 2012–2016). In parallel to this (shown from the top downwards in Figure 1), model residential buildings with rectangular shapes, expressed by different external side ratios (ESR—the ratio of length to width as explained in Section 2.2.1) and number of floors, have been defined and then analyzed using the LCA methodology for three environmental indicators (cumulative energy demand (CED), global warming potential (GWP), method of ecological scarcity (UBP)), both when constructed in a traditional way as well as when the construction is based on the circularity-oriented approach. In the final step, for each indicator, the impact of the lowest and highest contributor of the circular buildings was subtracted from the impact of the highest contributor (conventional buildings) and then multiplied by the calculated net change of the residential built environment, in order to estimate the range of savings, respectively, that can be achieved at country level (extrapolated calculations).
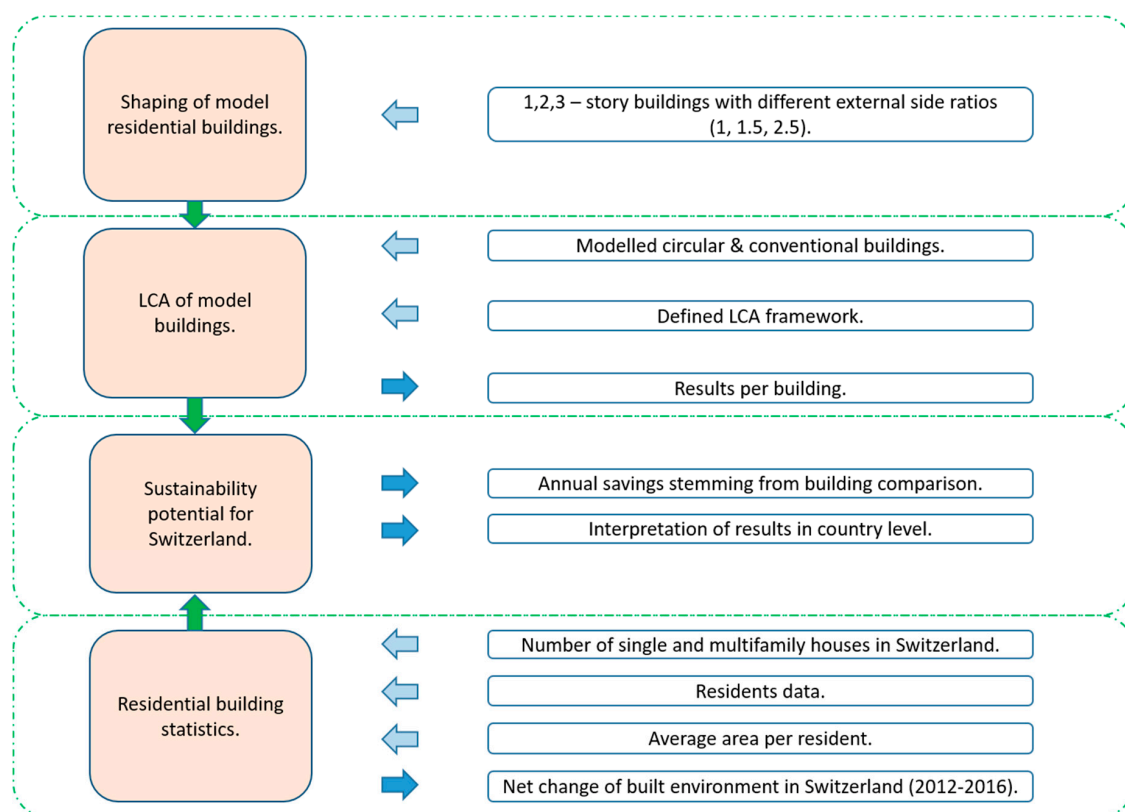

Figure 1. Stepwise procedure for estimation of Swiss sustainability potential.

2.2. Swiss Residential Building Sector

The Swiss building sector consists of a variety of buildings with either a clearly specified or a mixed function. A more detailed picture of the Swiss building sector is provided by the building and housing industry report published by the Swiss Federal Office for Statistics [35]. From the various building categories reported there, only those representing 100% residential use are taken into account

for this study. These categories are then allocated either to the group of single family houses (SFH) or multi-family houses (MFH). Within the Swiss building sector, the majority of construction materials (i.e., about 62%) can be found in residential buildings, whereof 44% are integrated in the MFH category [36]. Furthermore, Swiss residential buildings constructed after 1960 are made mainly out of concrete—a statement that holds true even for more recent buildings (i.e., buildings constructed from 2000 and onwards), with 54% of their primary structure consisting of concrete. Therefore, the conventional buildings in this study—portraying the traditional way of construction—are constructed with concrete as the base material.

2.2.1. Model Residential Buildings

In order to make the subsequent LCA calculations more straightforward, the various residential building forms were systemized into a limited number of model (residential) buildings, distinguishing them by ESR (i.e., the ratio of length to width) and number of floors. One of the objectives in this step of the study was to evaluate the influence of these two elements (i.e., ESR and the number of floors) on the overall LCA results of the building; and thus, to decide if these variations in shape and geometry need to be actually considered in such a type of study.

In the case of SFH, only floor numbers representing more than 3% of the total SFH in Switzerland (according to Table 1) were taken into account; all other values are considered extreme and were neglected. Therefore, SFH with one up to three floors were analyzed, portraying 98% of the total number of SFH, with an average total surface area of 120 m^2 in each case (more information in Section 2.2.2). Then, for the one-story SFH, such a variation of the ESR was applied—including ratios of 1 (i.e., a squarish shape), 1.5, and 2.5. These two variations (i.e., number of floors and variations of ESR) allow us to observe the actual influence of these two geometrical factors on LCA-related impacts. In the case of MFH, only one building type having 3 floors and a total surface area of 450 m^2 (more information in Section 2.2.2) is included in the present study, representing about 40% of the total MFH in Switzerland, as shown in Table 1. Data in Table 1 were personally communicated to us by the Swiss Federal Office for Statistics.

Table 1. Estimation of the development of the built environment for residential buildings of type "single family houses" (SFH) and "multi-family houses" (MFH) 2012–2016 in Switzerland.

Number of Floors	2012				2016			
	Absolute # of Buildings		% of Total		Absolute # of Buildings		% of Total	
	SFH	MFH	SFH	MFH	SFH	MFH	SFH	MFH
1	100,142	3453	10.41	<1	102,312	3853	10.34	<1
2	585,135	97,155	60.82	22.54	604,063	103,497	61.07	22.66
3	254,268	170,526	26.43	39.56	261,713	181,224	26.46	39.68
4	20,178	94,803	2.1	21.99	18,904	100,070	1.91	21.91
5	2126	38,467	0.22	8.92	2006	40,257	0.2	8.81
6	125	14,112	0.01	3.27	80	14,760	0.01	3.23
7	21	6406	<0.01	1.49	16	6657	<0.01	1.46
8	10	2848	<0.01	<1	4	3056	<0.01	<1
9	9	1346	<0.01	<1	0	1426	<0.01	<1
10+	1	1919	<0.01	<1	0	1952	<0.01	<1
Total	962,015	431,035	100	100	989,098	456,752	100	100

Table 2 reports the (geometrically) different buildings and their most important dimensions. The different ESRs where chosen in order to take into account the fact that buildings have different rectangular shapes. Based on the ESRs, the average area for SFHs (120 m^2) and MFHs (450 m^2) exhibited in Section 2.2.2 and the number of floors of each building category (with all floors having the same area), the area of each floor was calculated along with the outside dimensions of each floor. Afterwards, two construction techniques—i.e., one based on the traditional construction technique (with concrete as the base material) and one based on the previously described circularity-oriented

construction technique (based on timber)—were applied in the study. Circular buildings were modeled based on all values reported below, while traditional SFH buildings were modeled with an ESR of 1.5 for the various number of floors (the reason for this choice can be seen in the Section 3.1). The choice of timber as primary material for the latter building types is obvious, considering that (as long as it is used correctly) it can be recovered and recycled fully within the biological metabolism. As already mentioned, the UMAR unit installed in the NEST building is used as the basis for the latter technique (which utilizes also timber as primary material), while for the traditional construction technique, the key elements that need to be distinguished (i.e., outside wall, inside wall, floor, and roof) were taken from the "Bauteilkatalog" database [37], representing commonly used construction elements in Switzerland. In detail, the following elements from this database have been used for the traditional buildings in this study: concrete outside wall W08, brick-based inside wall W25, concrete roof type D01, and the concrete floor type B01.

Table 2. Dimensions of the modeled single family houses (SFH) and multi-family houses (MFH).

Building Parameters	SFH					MFH
Number of Floors	**1**			**2**	**3**	**3**
ESR	**1**	**1.5**	**2.5**	**1.5**	**1.5**	**1.5**
Area per floor (m^2)	120	120	120	60	40	150
Length (m)	10.95	13.4	17.4	9.5	7.75	15
Width (m)	10.95	8.95	6.9	6.3	5.15	10

2.2.2. Net Change of the Built Environment

Our interest in the Swiss residential building sector lies in the net changes of the stock of these two groups (i.e., SFH and MFH). For this study, the period between 2012 and 2016 was used in order to calculate the average net change (in km^2 of surface) in the residential area in Switzerland for these kinds of buildings. Using a period instead of a single year helps to avoid obtaining misleading results due to, e.g., a (single) bad or good year of the construction sector.

Within the covered period, the total net change in the residential built environment was calculated by multiplying the net change of residents in these houses in Switzerland with the average living area per resident (both types of data were personally communicated to the author by the Swiss Federal Office for Statistics). Table 3 reports the number of residents and the calculated built environment for 2012 and 2016, respectively. The net changes in both parameters were calculated by subtracting the 2012 values from the 2016 ones, yielding 5.48 km^2 for SFH, and 18.32 km^2 for MFH, respectively. The average area per building category was estimated to be 121 m^2 and 467 m^2 for the SFH and MFH, respectively; but for simplicity purposes, the above-mentioned numbers have been adjusted to 120 m^2 and 450 m^2, respectively, as the dimensions of the buildings.

Table 3. Net changes of the key aspects of the Swiss residential building sector for 2012–2016.

Swiss (100%) Residential Buildings	Average Area per Resident (m^2)	# of Residents			Built Area (km^2)		
		2012	**2016**	**Net Change**	**2012**	**2016**	**Net Change**
SFH	51	2,246,691	2,354,077	107,386	114.58	120.06	5.48
MFH	48	4,069,389	4,451,085	381,696	195.33	213.65	18.32

2.3. LCA Framework

The LCA methodology was applied to the evaluation of the environmental impacts of the various model residential buildings (with either of the two construction techniques). LCA allows the quantification of the potential environmental impacts of a product or service throughout the entire life-cycle, from primary material extraction and manufacturing to the final disposal and/or a

respective recycling step [38]. Therefore, LCA can be considered as an ideal tool in order to evaluate the environmental sustainability potential that lies behind a new construction technique such as the UM concept. In this study, the LCA framework was applied in respect with the European standard guidelines concerning the sustainability of construction works [39] and the Swiss guidelines for the calculation of grey energy embodied in buildings [40].

2.3.1. Goal and Scope Definition

The objective of LCA calculations is to assess the environmental impacts of the defined circularity-oriented buildings (based on timber) and to compare these impacts with those of conventional buildings (based on concrete) of identical shapes and sizes. The reference flow for all these calculations is "1 m^2 of gross floor area per one-year lifetime". The building's lifetime is assumed to be constant for the various default buildings at 60 years. Figure 2 illustrates the system boundaries, as defined by the EN15804 standard, for both levels of analysis in a summarized form.
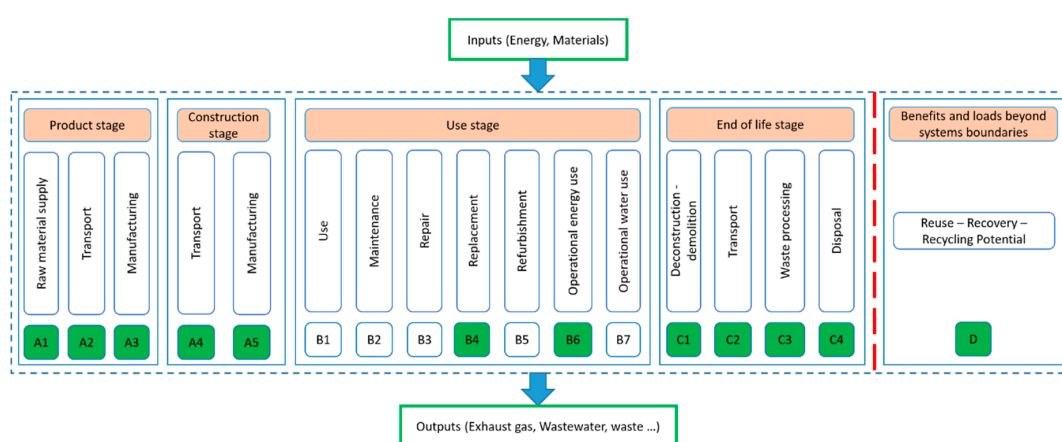
Figure 2. Life cycle assessment (LCA) stages according to EN 15804. The steps included in this study are those highlighted in green.

The steps covered in this study are those highlighted in dark green (i.e., A1–A5, B4, B6, C1–C4, D). The software tool used for this entire analysis was SimaPro 8.5.2 and the database containing the background processes used in this study was Ecoinvent, version 3.4 [41].

2.3.2. Life Cycle Inventory (LCI) Modelling

In this next step, all input and output flows of the system under investigation were identified and quantified, i.e., all the materials (for the initial construction as well as its replacements during the lifetime of the building), the energy consumption (all along the life-cycle), the treatment of the generated construction and demolition waste (CDW), the construction and the demolition processes, as well as all the transports from—and to—the building site. The entire inventory and its underlying assumptions can be found in the Supplementary Materials.

In order to be as adequate as possible for the comparison of the model buildings, only the elementary materials comprising the basic construction elements (i.e., inside and outside walls, roof, floor, as well as all intermediate floor slabs) have been considered in this study. Paints have been excluded from the study, due to the variety of paints that could potentially be used on both buildings (with no effect on the overall sustainability potential) and their generally low relevance compared to the overall building impacts. Furthermore, doors, window frames, and stairs were excluded from the study in accordance with the Swiss Standards for the calculation of the grey energy of buildings (i.e., with SIA standard 2032 [40]). Mechanical and electrical equipment has also not been considered in the LCA calculation, since it could be assumed to be similar in both cases; thus, not contributing to

the environmental sustainability potential of a change in the construction technique, which was the focus of this study.

The very last step (i.e., the module "D"—reuse/recovery potential) reports the avoided environmental impact that stems from a reuse and/or recovery of materials after the demolition of the buildings. This can obviously only be applied to materials that can also serve as substitutes for similar materials in another building and have reached their end-of-life [42]. This life-cycle stage is outside the actual system boundaries of a building and needs to be reported separately from the other stages, as it represents an array of activities that is not associated with the buildings under examination [43] (see also Figure 2). For the circular buildings, it was assumed that after deconstruction, 100% of the various materials could be recovered and used again in a similar manner; representing one of the key characteristics behind this new construction concept that considers a building as a material depot for future construction.

Finally, the materials comprising both types of buildings were assumed to be normally produced, by consuming natural resources, with no recycled content or directly reused materials taken into account. In other words, this means that the study considers the very first life-cycle of these materials and consequently the first stage of UM, where all materials are produced from scratch. Thus, the environmental potential of UM and recycling at the individual building level is expressed in the "module D" calculation.

Energy consumption can be divided into two categories: (a) energy consumption associated with the materials production and building construction phase (i.e., embodied energy), and (b) operation energy consumed during the use phase of the building [44]. The importance of the former, related to the total impacts of a building, will rise substantially in the future [45] not only due to increased material input (passive building) [46] but also because buildings are projected to exhibit increased energy efficiency [47] and to cover a significant fraction of their energy demand from renewable energy sources. The building's energy consumption is based on the status quo in this study, meaning that the operational energy in the use stage is expected to be among the most significant contributors to the overall impact of a building, if not the most significant of all [48–50]. This is because energy is a yearly input during a building's actual use phase, in contrast to the material input, which is mainly introduced at the beginning of the life-cycle of the same building. The magnitude of the related environmental impacts depends, however, very much on the actual production technology for the consumed electricity and heat. A thorough assessment of this energy demand is outside the scope of this study, which focuses on the potential in a new construction concept that strives towards urban mining. The operational energy has been included for completeness purposes. Thus, as a first approximation, a similar energy consumption of both types of buildings is assumed; consumption that was assessed using the SIA 2024 building tool [51], which provides reference values for all aspects of building-related energy consumption, considering the electricity country mix of Switzerland provided in the Ecoinvent database v3.4 [41].

2.3.3. Life Cycle Impact Assessment (LCIA)

For the impact assessment step, in accordance with the Swiss construction industry [52], the following three impact categories were considered in this study, representing many of the most relevant environmental issues in our society today—and through the third factor in particular, a "true and fair view" of the overall potential environmental impacts can be obtained (at least from the point of view of the Swiss Government, who commissioned this latter method):

- CED (cumulative energy demand). This impact factor shows the total energy required to deliver a product. However, only the non-renewable fraction is displayed, as this is the relevant part. The value is often referred to as "energetic footprint" and is reported in MJ energy [53,54].
- GWP (global warming potential). This indicator estimates the carbon footprint for a product or service by assessing various GHG emissions throughout their lifetime. The indicator is reported in kg of CO_2 equivalents [55].

- UBP (method of ecological scarcity). The Swiss-based method of ecological scarcity (EC) assesses the total environmental impact in the context of LCA [56]. Central parameters of the method are the so-called eco-factors, which indicate the environmental impacts of a released emission or an extracted resource in the unit of "Environmental Impact Points" (in German "Umweltbelastungspunkte", UBP) per unit of quantity. The value aggregates and assesses a variety of environmental impacts in a "true and fair" view, collectively referred to as the Ecological Footprint.

3. Results and Discussion

As for results, two different levels are distinguished by presenting first (see Section 3.1) the results for the individual model (residential) buildings when applying either the circularity-oriented or a traditional construction technique for each of the individual buildings. Then, in a second step (summarized in Section 3.2), the resulting environmental sustainability potentials for the whole Swiss residential building stock are reported. Absolute values are reported in Table S10 of the Supplementary Materials.

3.1. Model Residential Buildings

Figures 3–5 show the impacts of the three impact categories examined—per functional unit—for each of the individual (model residential) buildings, split into the different life-cycle stages and relative to the impacts of the option with the highest impacts (i.e., traditional one-story SFH with ESR of 1.5). The total impacts of the highest contributor (i.e., 100%) represent 379.5 MJ-Eq/(m^2×a) for the CED, 15.2 kg CO_2-Eq/(m^2×a) for the GWP, and 21,950 Eco-points/(m^2×a) for the EC method.
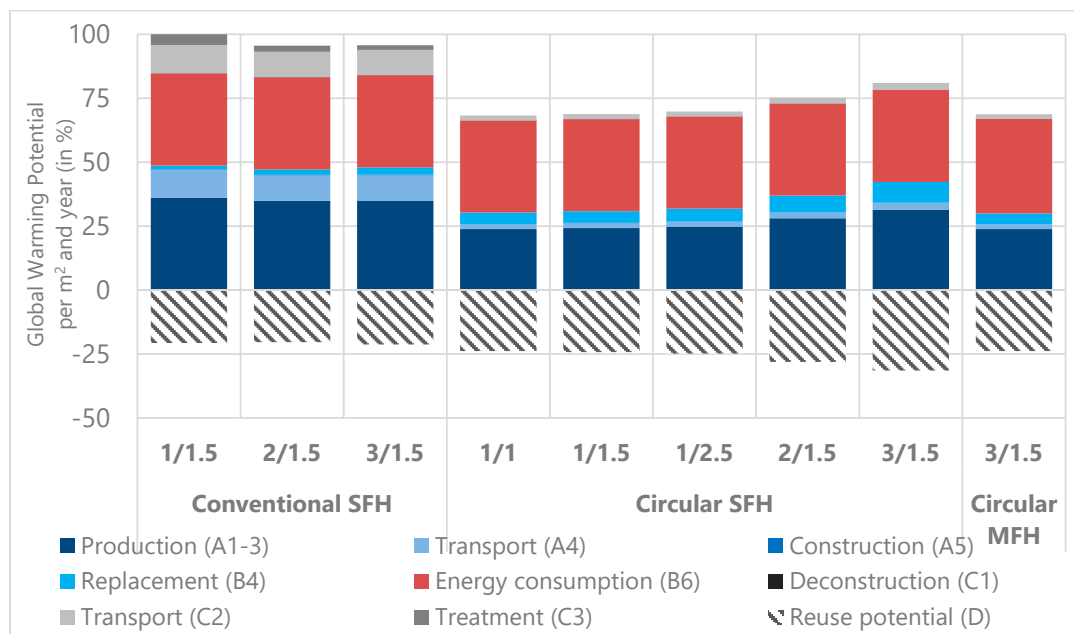

Figure 3. Environmental impacts per m^2 and year of the various model residential buildings examined in this study. Shown is the global warming potential (in kg CO_2-Eq), expressed in % of the model building with the highest impact (i.e., one-story traditional SFH with an external side ratio (ESR) of 1.5).
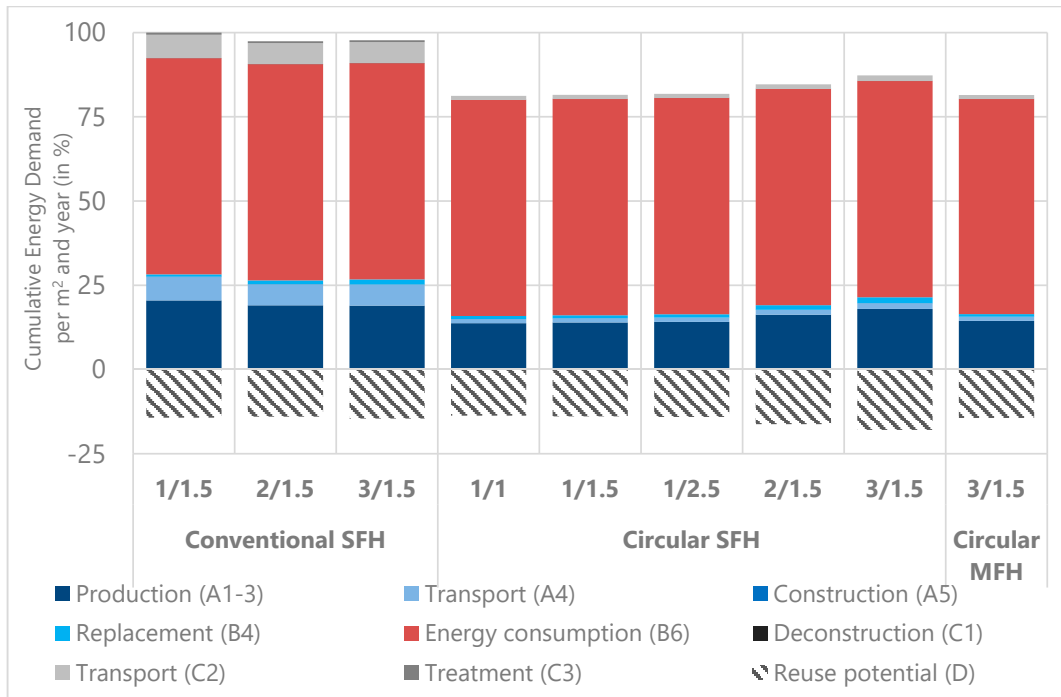
Figure 4. Environmental impacts per m² and year of the various model residential buildings examined in this study. Shown is the cumulative energy demand (in MJ-Eq), expressed in % of the model building with the highest impact (i.e., one-story traditional SFH with ESR of 1.5).
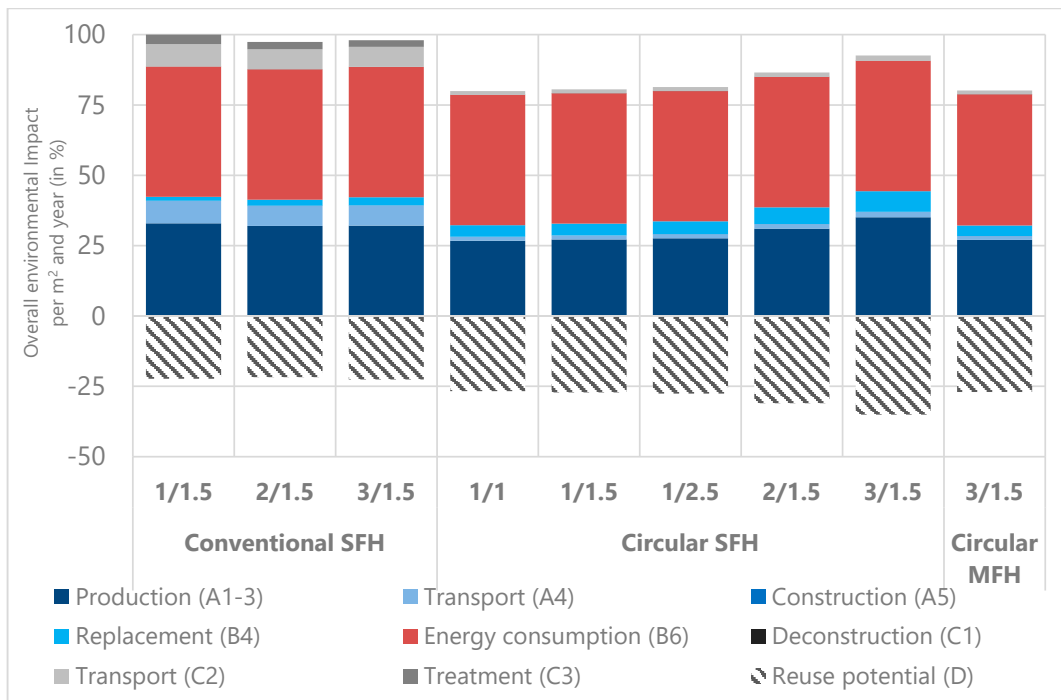

Figure 5. Environmental impacts per m² and year of the various model residential buildings examined in this study. Shown is the overall environmental impact, expressed with the method of ecological scarcity (in Swiss Eco-points), expressed in % of the model building with the highest impact (i.e., one-story traditional SFH with ESR of 1.5).

As expected, the traditional buildings made of concrete have the highest total environmental impact comprised by all indicators considered in this study (16% total difference between highest

impact one-story traditional SFH and low impact one-story SFH with ESR of 1.5 for CED, 32% for GWP, and 20% for UBP, respectively). Furthermore, the impact of the geometry (different ESR for the one-story circular SFH) does not influence the total impact of the buildings, as the values seem to have negligible differences from one another, which is why conventional buildings with different ESRs were not modeled. The number of floors of the circular SFHs made of wood does not have a strong effect on the CED indicator (only 6% difference between highest and lowest circular SFH), but the profile is different for the GWP and UBP indicators (nearly 13% impact difference between highest and lowest circular SFH contributor). The circular MFH seems to have lower impact than some of its SFH counterparts, due to the fact that the amount of materials and energy consumption—the two most essential stages of the LCA—are distributed over a much larger space than the SFH (total area 450 m^2 and 120 m^2, respectively). In addition, no conventional MFH was modeled in this study; therefore, it is not possible to draw a comparison between the two construction techniques for these types of buildings. Nevertheless, considering that the circular MFH shows on the level of its impacts per m^2 only minor differences from the circular SFHs, and thus the country potential results will not be affected, the formation and subsequent comparison of a circular MFH with a conventional one could be neglected.

Energy consumption dominates the CED indicator (over 60% for all buildings), but that does not apply to GWP and UBP (nearly 36% and 46%, respectively). The reason for that is the environmentally friendly energy mix utilized in this study. Finally, the similar impact per indicator for all buildings obtained from the analysis is due to the fact that the same standard values from SIA 2024 standard were used irrespective of the type of building under consideration.

Material production impact—as the second most dominant stage—ranges from 24–35% for GWP and UBP indicators for the circular SFHs, while for the CED the impact profile of the same buildings looks less significant (13–17% range). Furthermore, the particularly high impact (even for the circular buildings) stems from the assumption that materials for all buildings were produced from scratch. Hence, no reused or recycled materials (with lower impact) were introduced at the beginning that could possibly reduce even further the impact of this stage, illustrating that this represents the starting point of materials' life and the first stage of UM. In current LCA practice, material production is usually allocated to its first consumer. By applying this principle, the estimation of the sustainability potential remains on the conservative side on the country level; therefore, this assumption was accepted for the present study.

The reuse potential (i.e., module D) is quite high for circular buildings (at least 24%, especially for GWP and UBP). One hundred percent material recovery from the deconstruction of the wooden buildings and direct reuse of the stored materials in different construction projects are the reasons for the high avoided environmental impact. Even though the assumption of 100% direct material reuse may be controversial, it is in fact in line with the objective of this study, as it displays the maximum potential benefits that could be achieved. In this type of study, the maximum avoided environmental impact can only be calculated by using such an optimistic scenario. From an LCA point of view, even if a more realistic scenario was taken into account, the total impact of the buildings would remain at nearly the same level considering that the treatment of circular materials would, on the one hand, increase the potential environmental burdens of the end-of-life stage, but, on the other hand, decrease the potential environmental benefits (in stage D), as less material would be available after a post-treatment [33]. The same argument applies to the materials reused in conventional buildings. Finally, for the traditional buildings, the over 20% reuse potential for GWP and UBP shows that there is significant potential in utilizing an appropriate UM strategy for conventional materials too.

Last but not least, a further benefit of introducing such a design-for-disassembly concept is illustrated by the fact that the impact of the construction of the circular buildings represents only 5% of the respective impact for a traditional building construction in the case of the CED, and only 2% in cases of GWP and UBP; keeping in mind that the impacts of this stage represent usually only a tiny fraction of buildings' total impact.

3.2. Country Level Sustainability Potential

Based on the impacts from the various default buildings above, the overall environmental sustainability potential obtainable from a shift in the construction technique for an entire country can then be quantified—away from today's linear status quo towards a future, more renewable way, based on a circular approach. For this, the difference between the impact of the one-story traditional SFH with ESR of 1.5 (i.e., the highest contributor) and the lowest and highest impacts of the circular buildings is calculated in order to estimate the maximum and minimum savings, respectively, that can be attained. Taking such a range instead of a single value is more appropriate to cope with the high variability that can be seen in building geometry within a country. Afterwards, the multiplication of those savings with the net change of the building environment, as shown in Table 3, provides us with the sustainability potential for all of Switzerland for the reference period 2012–2016; the results for each indicator are displayed in Figure 6.

Figure 6. Range of the sustainability potential for Switzerland (shown for each indicator—results represent each time the savings achieved during the reference period of 2012–2016).

These results exhibit the amount of savings that could be achieved by a potential change in construction practice (including concepts such as design-for-disassembly and material recovery) of the Swiss residential building sector (68–117 kt CO_2 –Eq, 318–471 GWh, and 38,000–105,000 Million UBP). The results are meant to be a first, rough estimation of this potential due to the assumptions that are attached to it. For instance, calculating for the country level, it is indirectly assumed that the net change of the built environment is due to construction of either concrete or timber-based buildings (omitting all further types of building materials). In addition, the stages of operational energy consumption (B4) and reuse (D) of the considered LCA were excluded from the calculation of this potential. The reason for this exclusion is that the energy consumption of the buildings does not fit into the concept of seeing the building as materials stock. The reuse potential was also excluded because it refers to a possible reuse of materials, which is outside the system boundaries as defined above in the goal and scope. Hence, the calculated potential not only refers to material stages but also provides a holistic approach for both types of buildings.

Last but not least, significant further types of residential buildings were not included in the LCA (such as, e.g., two- and four-story MFH). Nevertheless, it is essential to indicate that despite the choice of these residential buildings as representatives of Swiss residential building stock, the net change in the built environment was calculated by including all buildings mentioned in Table 1.

4. Limitations

The proper integration of a circular economy and its core principles can lead not only to energy and emission reduction and its related, overall environmental benefits, but also to resource conservation [57,58]. However, there are some pressing issues that have so far been ignored and need to be addressed in further studies. From a strategy point of view, only the Swiss residential

building stock was analyzed, leaving other areas of application, such as offices, industrial buildings, or buildings with a mixed function, out of scope. For a complete picture, the whole building stock must be identified as a material store, not just a fraction of it. In addition, the shapes introduced in this study are overly simplistic. Possible variations of shapes and geometries could also be a crucial point for a refined LCA estimation of the building stock.

From an LCA point of view, there are further points that need to be considered. This study makes an LCA of circular buildings by assuming that all materials were normally produced, without considering (partially or fully) recycled content in any of the materials or direct reusability of the materials stemming from a previous use. In that way, it represents the first life-cycle of the materials and the first (circular) stage of the UM concept and results in a conservative estimation of the country level potential. Further investigations should be conducted pertaining to the environmental impact of further stages (second, third, etc. life-cycles) originating from the application of the UM concept as well as from the potential impact and benefits of reuse [59]. When talking about applying the UM concept to real projects (such as the UMAR unit), this cycle of materials should be considered in possible LCA, as it will further reduce the impact of the said project (because part of the chosen materials will be mined and recycled or will be directly reused) and would subsequently increase the sustainability potential at the country level.

Furthermore, when a material is reused in a different project after its treatment, it results only in impacts due to the transport to the location of its reuse. In other words, when a material is produced and utilized for the first time, its (first) consumer has to bear all the impacts associated with the production and receives no credit for choosing a reusable material. Consequently, the second consumer acquires a material with full or partial lifetime attached to it, but with a much reduced impact, meaning that the reporting of the recycling/reuse potential (module D) of such materials, in contrast to the current approach considered and used on this manuscript (the benefits from recycling/reuse are reported together with the impacts of considered modules A–C but cannot offset them), requires further investigation [60]. The application of such a new approach would be in favor of future UM buildings and should further increase the potential savings, coming from a switch in construction practice both at the building and country levels.

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