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PAPER

Environmental savings from concrete reuse: examining the limitations and optimal practices for cutting thresholds of concrete building components for reuse

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Abstract

Concrete, a widely used construction material, presents both opportunities and challenges for promoting environmentally responsible practices. This research focuses on the concept of concrete reuse as a sustainable strategy, examining the limitations of cutting dimensions. To investigate the greenhouse gas (GHG) emissions associated with preparing concrete for reuse, a mathematical model was developed considering several factors, such as transportation emissions, energy used in cutting, and the effects of varying cutting performance and energy sources. By incorporating real-life data and connecting with industrial practices, this study establishes a screening standard to determine the minimum cutting size for concrete reuse. The results indicate that the ratio of transportation distances for the reuse case versus the new production of concrete case has an influence on the minimum cutting size for concrete reuse. Moreover, the cutting size itself significantly impacts the overall GHG emissions of the reuse strategy. We offer practical insights for industry stakeholders to optimize concrete reuse practices and effectively reduce GHG emissions. As further research explores cost-effectiveness and on-site case studies, the potential for large-scale implementation of concrete reuse has become increasingly promising. Thus, concrete reuse has emerged as a viable and effective approach to sustainable construction, provided that the minimum cutting dimensions are carefully considered.

1. Introduction

The construction industry plays a significant role in global resource demand, accounting for approximately 35% of global energy use and 38% of energy-related greenhouse gas (GHG) emissions [1, 2]. Furthermore, it contributes nearly 50% of the world's annual resource consumption [3] and generates a substantial portion of waste, with one-third originating from Europe [4]. The exponential growth of material stocks in buildings, infrastructure, and durable goods from 1900 to 2010, increasing 23-fold [5], indicates the urgent need to address the environmental impacts of construction activities.

Concrete, widely used in construction [6], offers high performance and availability [7]. However, the production of new concrete entails substantial energy, resource consumption, and CO_2 emissions [8]. Moreover, there are concerns regarding the future scarcity of raw materials, such as gravel and sand [9]. Demolition activities also result in significant waste, with concrete and stony materials accounting for more than 80% of construction and demolition waste in Europe [7, 10–12]. Although researchers have endeavoured to alleviate these effects by extending the operational lifespan of concrete components or exploring alternative binding agents [13–15], the implementation of these strategies has been hindered by issues relating to availability, cost, and regulations [16, 17]. Currently, there is emerging momentum towards advocating the principles of a circular economy and promoting material reuse in the built environment [18].

In the circular economy framework, Hendriks' strategies for the construction sector suggest repurposing obsolete concrete as backfill or aggregate substitutes, termed 'recycled concrete' [19–21]. This approach aids in waste minimization and resource preservation but raises concerns due to its similar CO_2 footprint, which is linked to higher cement usage [22–24]. Reuse strategies involve dismantling concrete components and integrating them into new structures, preserving their original value while minimizing reprocessing [25]. This approach is preferred over recycling because it extends the material's lifespan and reduces the demand for new resources, consistent with sustainable construction principles. Research shows that compared with new equivalents, reused construction materials can achieve an 80% to 90% reduction in GHG emissions [26–29].

The reuse of concrete is pivotal in construction, offering environmental, economic, and social advantages. It notably reduces waste, pollution, energy use, GHG emissions, and manufacturing costs, supporting the circular economy by promoting material reuse [26, 30, 31]. Particularly in load-bearing structures, such as slabs, which usually represent 65% of the environmental impact of structural elements, repair, strengthening, and adaptation are key to decreasing the environmental footprint of new constructions. The reuse of precast concrete panels has been widely investigated in Europe since the last century. Several studies have discussed the reuse of precast elements from deconstructed buildings in new construction projects, demonstrating both the technical feasibility and environmental benefits of this approach [32–37]. The reuse of cast-in-place concrete, though less extensively explored, has shown promise with pioneering projects, such as the Udden project in Sweden [38]. This project showcased the practical application of reusing large concrete elements from demolished buildings in new residential constructions, highlighting significant reductions in CO_2 emissions and energy use, thereby reinforcing the viability of this practice [38–40]. Contemporary research has also expanded the scope of concrete reuse to include infrastructural applications. For example, garden tiles have been upcycled into self-supporting walls [41], train platform tiles into courtyard pavement [42], and hollow-core slabs from office buildings have been considered for new residential projects [36]. Since the late 2010s, multiple projects have explored the reuse of elements from cast-in-place structures with promising applications, though typically in a downcycling manner. Key examples include the reuse of walls and foundation mats as prestressed blocks in a footbridge [8], the repurposing of building slabs into parking slabs [12], and the transformation of building elements into weight foundation blocks [43], which substantially decrease the global warming potential compared with the use of recycled concrete or steel [8, 12]. As concluded in the comprehensive review work of C. Küpfer [25], concrete reuse practices have evolved from small-scale applications using precast components in the latter half of the last century to larger implementations since the early 2000s and, most recently, to prototypes reusing cast-in-place pieces over the past decade.

With advancements in cutting tool technology and the urgent need for carbon reduction, reuse has emerged as a prominent trend. However, as mentioned in previous studies [25], there is a research gap regarding the evolution of cast-in-place concrete reuse practices, and the efficacy of the cutting process remains a significant question [25]. Previous research has shown that the labour-intensive, time-consuming, and nonoptimised nature of the reuse strategy often hinders its application in real-life scenarios [12, 44]. Various studies have proven that reuse strategies generally reduce environmental impact. For example, the Re:crete footbridge demonstrates a 71% reduction in global warming potential compared to a recycled concrete alternative, and reused-concrete parking pavement shows an 82% reduction, although the outcomes are case dependent [8, 12, 25]. Similar to recycling concrete as an aggregate, which may not yield significant carbon savings due to high energy consumption [22, 23], **the question arises as to whether there is a limit to cutting concrete beyond which the benefits diminish.** A key factor affecting the quality and reuse potential of concrete is the cutting dimension. This dimension influences the element's suitability for reuse, strength, and durability. With smaller cutting dimensions, increased cutting times potentially lead to higher GHG emissions [12].

In this study, we explore how transportation and cutting energy impact the GHG emissions associated with preparing concrete for reuse [45]. We created a mathematical model to identify the minimum cutting dimensions for reusing concrete, aligning our findings with real-world industrial practices. Our goal is to define the cutting limits and best practices for concrete reuse, aiding in the development of strategies that reduce environmental impact and enhance sustainability in construction. The insights gained will guide industry stakeholders in adopting concrete reuse methods and fostering resource efficiency and environmental stewardship.

2. Method

To identify the primary contributors to GHG emissions in concrete reuse, we centred our model on specific evaluative parameters, excluding several factors, such as contamination, waste, material quality, and longevity. The established criteria thus represent the minimum benchmarks for reuse. This study focused on GHG emissions during concrete cutting and preparation using specialized equipment, such as the DST20-CA diamond wall saw produced by HILTI AG as a demonstration [7, 46, 47] (HILTI DST20-CA), and considered the transport of the cut concrete. We utilize life cycle assessment (LCA) [22] to thoroughly evaluate the environmental impact of operating cutting equipment on transporting concrete pieces as well as the production of concrete.

The methodology for this study is divided into several key components to comprehensively evaluate the environmental impacts and practical implications of reusing concrete components. The primary focus is on developing a mathematical model to assess the energy consumption and carbon emissions associated with the reuse of concrete, specifically considering the cutting dimensions and transportation requirements. This model helps determine the optimal cutting dimensions for concrete reuse, ensuring a balance between environmental impact and material efficacy. The study includes expert interviews for empirical insights [47].

2.1. Defining the mathematical model

This section presents our mathematical model designed to evaluate the GHG emissions from reusing concrete load-bearing elements versus producing new elements. GHG emissions across a concrete beam lifecycle are analysed in two scenarios: (i) manufacturing new concrete components and (ii) reusing concrete, considering cutting and transportation. The model uses case studies of representative concrete beams or walls, incorporating data on engineering specifications, material densities, emission factors, cutting parameters, transportation distances, and energy consumption of machinery.

2.1.1. Inputs and assumptions

In this section, we provide a detailed overview of the model's input parameters, which are categorized into two subsections: one for specifications related to the reuse of concrete elements and the other for technical details of the concrete cutting machine.

Concrete and dimensional parameters: Taking a load-bearing beam as an example, the cutting length, beam width, and beam height are denoted as l_{cut}, w_{beam}, and h_{beam}, respectively, as shown in the top diagram of figure 1. The beam length is represented as l_{beam}. The corresponding volume of beam V_{cut} is calculated by

$$V_{\mathrm{cut}} = l_{\mathrm{cut}} w_{\mathrm{beam}} h_{\mathrm{beam}} \tag{1}$$

Material Parameters: The material densities and weights are calculated accordingly. For instance, for the weight of a concrete beam, the following equation is used:

$$w_{\mathrm{beam}} = V_{\mathrm{beam}} \rho_{\mathrm{beam}} \tag{2}$$

Transportation Parameters: For the new concrete case, the distance from the concrete manufacturing factory to the site is represented by d_{new} (in km). Meanwhile, for the reuse case, the total transportation distance is denoted as d_{reuse}, which is normally be the distance from the extraction site to the storage location and then to the new construction site.

Concrete cutting machine and blade parameters: Here, v_{cut} is the cutting speed of the blade, $\mathrm{lifetime}_{\mathrm{blade}}$ is the lifetime of the blade, d_{blade} is the diameter of the blade, t_{blade} is the thickness of the blade, ρ_{blade} is the density of the blade, and w_{blade} is the weight of the blade. The span of the blade is calculated as follows:

$$\mathrm{span}_{\mathrm{blade}} = \frac{\mathrm{lifetime}_{\mathrm{blade}}}{v_{\mathrm{cut}}}. \tag{3}$$

The weight of the blade is given by the following relation:

$$w_{\mathrm{blade}} = \pi \left(\frac{d_{\mathrm{blade}}}{2}\right)^2 t_{\mathrm{blade}} \rho_{\mathrm{blade}} \tag{4}$$

Wall Saw Parameters: The power of the wall saw machine is represented by P (in kW), and the weight of the machine is denoted as w_{machine}. The inputs for the cutting tool are based on the actual performance utilized

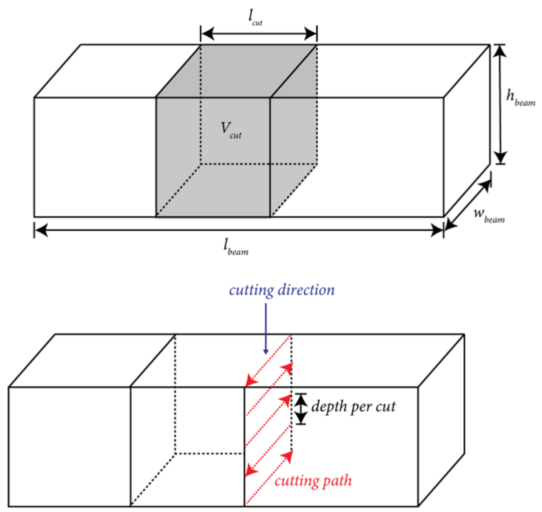

Figure 1. Visualization of beam sizes and cutting directions.

in this research, as it can be considered the best technology available for this purpose; further detailed rationales are provided in the appendix.

Cutting Parameters: This study considered two cutting speeds, fast and slow, along with their respective cutting areas. The cutting speed is determined based on on-site experience working with different types of load-bearing components. Let v_{fast} be the fast-cut speed area for normal reinforced concrete components with light aggregates and v_{slow} be the slow-cut speed area for heavy reinforced concrete components with hard aggregates.

2.1.2. Minimum solution model

Our investigation consists of finding a solution that balances the GHG emissions of reusing and producing new concrete. We utilize numerical methods, particularly the '*f*Solve' function, which is a Python function within the SciPy library [48] used for finding numerical solutions to systems of nonlinear equations, to pinpoint the exact point where these GHG emissions intersect. This intersection point serves as a critical threshold, indicating the ideal beam size that aligns the environmental trade-offs between reusing and producing new concrete.

The calculation of the solution hinges on the following equation:

$$l_{\text{min. cut}} = f\text{Solve}\left(\text{GHG}_{\text{reuse}} - \text{GHG}_{\text{new}}\right) \tag{5}$$

$\text{GHG}_{\text{re}-\text{use}}$ encapsulates the total GHG emissions of reusing concrete, and GHG_{new} encapsulates the GHG emissions associated with producing and transporting new concrete, which are expressed in $\text{kgCO}_2-\text{eq.}$ and calculated with the impact assessment method (global warming potential over 100 a, as suggested by the IPCC in 2021) and the LCA database Ecoinvent 3.10 [49].

2.1.2.1. Total GHG emissions associated with the production of new concrete

GHG_{new} refers to the GHG emissions associated with producing and transporting new prefabricated concrete:

$$\text{GHG}_{\text{new}} = \text{GHG}_{\text{beam}} + \text{GHG}_{\text{new transportation}}. \tag{6}$$

Similarly, the GHG emissions for transporting new concrete are calculated by multiplying the distance, the weight of the new concrete (converted to metric tons), and the GHG emissions for trucks:

$$\text{GHG}_{\text{new transporation}} = w_{\text{total}} d_{\text{new}} \text{GHG}_{\text{lorry}}. \tag{7}$$

The GHG emissions factor for manufacturing the new concrete load-bearing element is then calculated by multiplying the GHG emission factor by the weight of the element:

$$\text{GHG}_{\text{beam}} = w_{\text{total beams}} \text{GHG}_{\text{reinforced concrete}}. \tag{8}$$

The total weight of a concrete beam to be transported for reuse is determined via equation (9) by multiplying the maximum number of beams n_{beam} that can fit in a lorry with a given lorry capacity (assuming that the lorry is fully loaded) and the weight of a single beam:

$$w_{\text{total beams}} = w_{\text{beam}} n_{\text{beam}} \tag{9}$$

$$n_{\text{beam}} = \min\left(\frac{\text{lorry space capacity}}{V_{\text{beam}}}, \frac{\text{lorry load capacity}}{w_{\text{beam}}}\right). \tag{10}$$

2.1.2.2. Total GHG emissions of reusing concrete

$\text{GHG}_{\text{reuse}}$ encapsulates the total GHG emissions of reusing concrete, accounting for both cutting-related and transportation emissions:

$$\text{GHG}_{\text{reuse}} = \text{GHG}_{\text{cut}-\text{total}} + \text{GHG}_{\text{reuse transportation}} \tag{11}$$

$$\text{GHG}_{\text{cut}-\text{total}} = \text{GHG}_{\text{cutting energy consumption}} + \text{GHG}_{\text{blade consumption}} + \text{GHG}_{\text{re}-\text{glue}} \tag{12}$$

$\text{GHG}_{\text{cut}-\text{total}}$ refers to the total GHG emissions associated with the concrete cutting process. It is determined by the summation of three distinct factors:

$\text{GHG}_{\text{re}-\text{glue}}$: The GHG emissions arising from regluing the reused reinforced concrete pieces, where α_{glue} is an approximate ratio of the percentage of new concrete or gluing material required to connect the cut pieces. The related emissions are calculated as follows:

$$\text{GHG}_{\text{re}-\text{glue}} = w_{\text{beam}} \text{GHG}_{\text{reinforced concrete}} \alpha_{\text{glue}}. \tag{13}$$

$\text{GHG}_{\text{cutting energy consumption}}$: The GHG emissions arising from energy consumption during the cutting process. It is calculated by multiplying the product of the cutting time (T_{cut}) and the GHG emissions factor for energy consumption ($\text{GHG}_{\text{energy}}$) by the power of the cutting machine (P), where diesel-generated power is set as the baseline scenario. Mathematically, this is represented as follows:

$$\text{energy consumption } E_{\text{cut}} = P T_{\text{cut}} \tag{14}$$

$$\text{GHG}_{\text{cutting energy consumption}} = E_{\text{cut}} \text{GHG}_{\text{energy}} \tag{15}$$

$\text{GHG}_{\text{blade consumption}}$: The GHG emissions stemming from the production and usage of the cutting blade. It is computed by multiplying the product of the blade weight (w_{blade}), the GHG emission factor for the blade ($\text{GHG}_{\text{blade}}$), and the ratio of the cutting time (T_{cut}) to the blade span ($\text{span}_{\text{blade}}$). The blade span represents the operational lifespan of the blade, which is determined by the product of the blade's cutting speed and its lifetime. The calculation can be expressed as follows:

$$\text{GHG}_{\text{blade consumption}} = w_{\text{blade}} \text{GHG}_{\text{blade}} \frac{T_{\text{cut}}}{\text{span}_{\text{blade}}}. \tag{16}$$

The bottom diagram of figure 1 shows the cutting path, indicating the cutting direction, depth per cut, and progression of the cutting passes. The process involves multiple cutting passes, each approximately 12 cm deep, with a crucial initial guide cut to ensure accuracy.

The cutting time for a reinforced concrete load-bearing component is calculated by first identifying the number of cutting passes needed. Then, the cutting time is computed via two methods: T_1, which is based on the cutting speed v_1, and T_2, which is based on the cutting speed per unit area v_2. A cut beam requires 2 cuts at both ends. The function returns the larger value between the two alternatives:

$$T_{\text{cut}} = 2 \times \max(T_1, T_2) \tag{17}$$

$$T_1 = T_{1\text{ cut}} + T_{\text{guided cut}} = \frac{L_{cut}}{v_1} N_{\text{pass}} + \frac{L_{\text{cut}}}{v_1/2} \tag{18}$$

$$T_2 = T_{2\text{ cut}} + T_{\text{guided cut}} = \frac{A_{\text{beam}}}{v_2} + \frac{L_{\text{cut}}}{v_1/2} \tag{19}$$

$$\text{cutting pass } N_{\text{pass}} = \frac{\text{cutting depth}}{\text{depth per cut}} \times 2 \tag{20}$$

$$\text{Cutting depth}: D_{\text{cut}} = h_{\text{beam}} \tag{21}$$

$$\text{length of cutting route}: L_{\text{cut}} = w_{\text{beam}} \tag{22}$$

$$A_{\text{beam}} = w_{\text{beam}} h_{\text{beam}} \tag{23}$$

where A_{beam} refers to the cross-sectional area of the cut. For the case of slabs or walls, the cutting time is calculated with a similar strategy:

$$T_{\text{cut}} = \max(T_1, T_2) \tag{24}$$

$$T_1 = T_{1\,\text{cut}} + T_{\text{guided cut}} = \frac{L_{\text{cut}}}{v_1} N_{\text{pass}} + \frac{L_{\text{cut}}}{v_1/2} \tag{25}$$

$$T_2 = T_{2\,\text{cut}} + T_{\text{guided cut}} = \frac{L_{\text{cut}} D_{\text{cut}}}{v_2} + \frac{L_{\text{cut}}}{v_1/2} \tag{26}$$

$$\text{cutting route length } L_{\text{cut}} = 2(w_{\text{wall}} + h_{\text{wall}}) \tag{27}$$

$$\text{cutting depth } D_{\text{cut}} = t_{\text{wall}} \tag{28}$$

$$\text{cutting pass } N_{\text{pass}} = \frac{\text{cutting depth}}{\text{depth per cut}} \times 2 \tag{29}$$

where t_{wall}, w_{wall} and h_{wall} denote the thickness, width and height of the concrete wall, respectively.

The GHG emissions for transporting a reused concrete beam are calculated by multiplying the distance, the total weight of the concrete beam (converted to metric tons), and the unit GHG emissions for the lorries (specified in the supplementary files).

$$\text{GHG}_{\text{reuse transportation}} = d_{\text{reuse}} w_{\text{total}} \text{GHG}_{\text{lorry}}. \tag{30}$$

Through rigorous calculations and thorough analyses, we have developed a straightforward tool to derive essential values for comparing reusing and new concrete production strategies, which enables us to achieve a balanced assessment and determine the solution based on specific cases and criteria.

2.2. Further analysis

2.2.1. Sensitivity analysis

To understand the robustness of the model, sensitivity analyses are conducted by varying key parameters, such as the transportation distances, cutting tool performance, and energy sources. This helps identify the most influential factors affecting the environmental impact of concrete reuse.

2.2.2. Extensive analysis of reused concrete slabs

Another specific focus of this study is the extensive analysis of reused concrete slabs. Key aspects include analysing typical slab thickness (e.g. 0.2 m) and the effects of varying the height and width of cut pieces, assessing their impact on energy consumption and GHG emissions using the DST 20-CA wall saw, and creating visualizations of GHG emissions differences for various slab sizes.

3. Results

Our investigation initially focused on the study of a reinforced concrete beam, examining transportation at the maximum load capacity of a standard lorry. We consider typical transportation distances in Switzerland, starting with fixed distances before exploring variations in distances, cutting performance, and energy usage. Additionally, we analyse the dimensional threshold for concrete slabs through a targeted case study. In this study, both reused and new concrete beams of identical sizes are considered to ensure a consistent basis for comparison. By doing so, we effectively compare the environmental impacts of manufacturing new concrete versus cutting existing concrete for reuse.

3.1. Results in the typical Swiss context for concrete beams

To visually illustrate our findings, we initially focused on reusing a load-bearing reinforced concrete beam with 2.5% steel reinforcement and lightly aggregated concrete as an example. The standard dimension of the example beams chosen for the analysis is 0.4 m × 0.4 m with a length of less than 8 m to be reasonably found within the range of common building structures and trucking capacities. For general applications, a diesel generator was used for the analysis together with a DST20-CA wall saw.

3.1.1. Assuming constant transportation distances for both scenarios

To understand the predominant impact of cutting length on the difference in GHG emissions, we first explored the results of fully loaded lorries transporting reused materials over a standard 100 km distance, which is typical in urban settings. In this analysis, the cutting length of the concrete beam was the only variable. At a fixed transportation distance for both cases, transportation impacts remain consistent for both

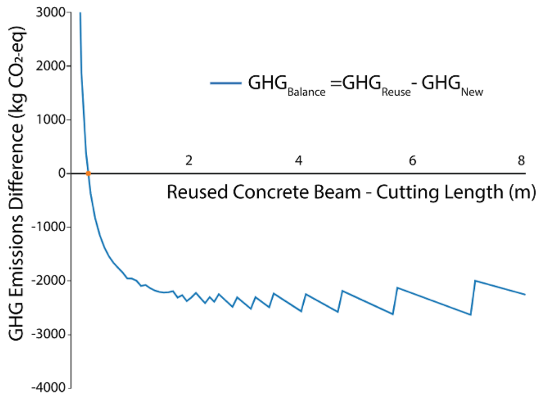

Figure 2. GHG emissions balance ($GHG_{reuse} - GHG_{new}$) of reused concrete beams over various cutting lengths, assuming equal transportation distances.

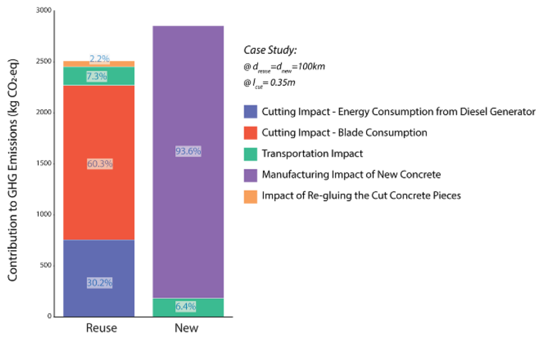

Figure 3. Sample GHG emissions contribution by category for reused vs. new concrete at a cutting length of 0.35 m for a 0.4 m × 0.4 m reinforced concrete beam.

reused and new concrete scenarios, which allows us to examine the effect of different cutting sizes on GHG emissions for both reused and newly manufactured concrete.

Figure 2 visually illustrates the difference between GHG emissions for reused concrete (GHG_{reuse}) and new concrete (GHG_{new}) across various cutting lengths. This analysis combines an analytical model with real-world data to ensure accuracy and reliability. The figure shows how the dynamics of the differences in GHG emissions change with cutting size. Small cutting volumes result in significant differences in GHG emissions due to high energy consumption and material waste during the cutting process. As the cutting size increases, a notable trend emerges: the overall difference in GHG emissions decreases, indicating more efficient material and energy use. The intersection point of the *x*-axis with the curve, derived using the '*f*solve' function mentioned in section 2.1.2 (minimum solution model), identifies the minimum cutting length as 0.3 m in the above settings. This threshold represents an extreme scenario in which the possibility of practical reuse remains viable even when considering the adverse effects of the cutting process.

The regular 12 ton, $9m^3$ lorry EURO6, when consistently fully loaded, stabilizes the volume and weight of the transported new concrete, thus maintaining a steady GHG emissions profile. In contrast, the GHG emissions from reuse decrease with increasing cutting size due to decreased cutting requirements and associated energy use. However, because beams are counted as discrete units, they do not fill the truck to the maximum capacity, as does fluid concrete, causing slight variations in the emissions difference curve. Essentially, larger cutting sizes lead to a smaller environmental footprint by minimizing the number of cuts needed.

3.1.2. Contribution analysis

Figure 3 illustrates the contribution analysis for GHG emissions related to a sample beam cutting length of 0.35 m, which is just above the minimum cutting length for a 0.4 m × 0.4 m beam size. The GHG emissions data for each impact and scenario are detailed in table 1. Compared with new manufacturing, reused concrete becomes more eco-friendly due to lower GHG emissions. The primary factors driving emissions in this context are blade consumption and energy usage during cutting.

Table 1. GHG emissions for reused concrete and new concrete production.

Reused concrete GHG emissions $kgCO_2 - eq$		%	New concrete GHG emissions $kgCO_2 - eq$		%
$GHG_{reuse\ transportation}$	182.13	7.3	$GHG_{new\ transporation}$	182.13	6.4
$GHG_{cutting\ energy\ consumption}$	757.39	30.2	GHG_{beam}	2672.61	93.6
$GHG_{blade\ consumption}$	1513.41	60.3			
$GHG_{re-glue}$	56.40	2.2			
Total GHG emissions:GHG_{reuse}	2510.06	100	Total GHG emissions:GHG_{new}	2854.75	100

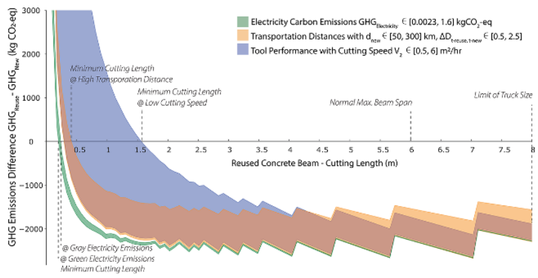

Figure 4. Differences in GHG emissions ($GHG_{reuse} - GHG_{new}$) of concrete components with varying energy sources' GHG emissions, transportation distances and cutting tool performance.

Conversely, for new concrete, manufacturing emerges as the main source of emissions, largely due to the significant CO_2 emissions from concrete production. When examining the GHG emissions at a sample cutting length of 0.35 m, the total GHG emissions for reused concrete (2510.06 $kgCO_2 - eq$) are lower than those for new concrete (2854.75 $kgCO_2 - eq$). This results in a net savings of 344.69 $kgCO_2 - eq$, which highlights the environmental benefits of reusing concrete despite the additional cutting processes. However, a more detailed contribution analysis at a cutting length of 0.25 m revealed a different scenario. At this shorter length, the total GHG emissions for reused concrete (3406.61 $kgCO_2 - eq$, which is 35% greater than that of the cutting length at 0.35 m) exceed those for new concrete (2844.68 $kgCO_2 - eq$) by approximately 561.93 $kgCO_2 - eq$. This increase is primarily driven by the greater energy (1056.60 $kgCO_2 - eq$) and blade consumption (2111.30 $kgCO_2 - eq$) impacts due to the greater frequency of cuts needed.

In short, while reusing concrete beams can lead to significant GHG emissions savings, the benefit of this process is highly dependent on the cutting length.

3.2. Sensitivity analysis with varying transportation, performance and energy

After understanding how the environmental impact and minimum cutting lengths relate in a simple scenario with fixed transportation, cutting speed, and energy source, it is important to note that these three main factors directly affect our model's inputs and results. Therefore, fixed ranges of values for these inputs are included to calculate the GHG emissions and to understand their influence, as shown in figure 4. The scenarios with varying cutting speeds and transportation distances assume the use of a diesel generator, as this is the most common power source for wall saws. This also mitigates the potential issue of grid electricity availability at demolition sites.

Transportation Variation: In practice, while reused concrete pieces can sometimes be transported directly from demolition to construction sites, they are more often moved to a storage location before being transported to their destination. This process generally results in longer overall transportation distances for reused concrete compared to new concrete, which is directly shipped from the factory to the construction site. To examine the implications of these transportation variations, we first define the ratio between the transportation distance for the reused component and the transportation distance for new concrete to the construction site as $\Delta D_{t-\text{reuse},t-\text{new}}$:

$$\Delta D_{t-\text{reuse},t-\text{new}} = \frac{d_{\text{reuse}}}{d_{\text{new}}}. \quad (31)$$

Regarding transportation, we vary the distance from the new concrete manufacturing factory to the construction site, with lengths ranging from 50 km to 300 km, and adjust $\Delta D_{t-\text{reuse},t-\text{new}}$ accordingly. Different travel distances significantly influence the range of impact differences, illustrated by the orange area in figure 4. When the transportation distances are identical, indicating that the GHG emissions from

Table 2. Variation of scenarios and corresponding minimum cutting length results.

Scenarios (setting all other parameters uniform)	Assumptions	Varying Parameters used	Results of minimum cutting length $l_{\text{min. cut}}$ ranges (m)
Transportation variation	• Diesel generator • $\text{GHG}_{\text{energy}} = 76.44\text{kgCO}_2 - \text{eq/hr}$ • $v_2 = 6\text{m}^2\,\text{hr}^{-1}$	$d_{\text{new}} \in [50, 300]\,\text{km}$, $\frac{d_{\text{reuse}}}{d_{\text{new}}} \in [0.5, 2.5]$	0.26 @$d_{\text{new}} = 300\text{km}$, $\frac{d_{\text{reuse}}}{d_{\text{new}}} = 0.5$ 0.41 @$d_{\text{new}} = 300\text{km}$, $\frac{d_{\text{reuse}}}{d_{\text{new}}} = 2.5$
Cutting tool performance variation	• Diesel generator • $\text{GHG}_{\text{energy}} = 76.44\text{kgCO}_2 - \text{eq/hr}$ • $d_{\text{new}} = d_{\text{reuse}} = 100\,\text{km}$	$v_2 \in [0.5, 6]\,\text{m}^2\,\text{hr}^{-1}$	0.30 @$v_2 = 6\text{m}^2\,\text{hr}^{-1}$ 1.56 @$v_2 = 0.5\text{m}^2\,\text{hr}^{-1}$
Energy source variation.	• Grid electricity • $v_2 = 6\text{m}^2\,\text{hr}^{-1}$ • $d_{\text{new}} = d_{\text{reuse}} = 100\,\text{km}$	$\text{GHG}_{\text{electricity}} \in [0.0023, 0.923]$ $\text{kgCO}_2 - \text{eq/kWh}$	0.18 @$\text{GHG}_{\text{electricity}} = 0.0023\text{kgCO}_2 - \text{eq}\,\text{kWh}^{-1}$ 0.24 @$\text{GHG}_{\text{electricity}} = 1.6\text{kgCO}_2 - \text{eq}\,\text{kWh}^{-1}$

transportation for both scenarios are equivalent, the only limiting factor becomes the cutting size. The potential variation in impact difference is notably wide, highlighting the significant effect of transportation on GHG emissions. Additionally, the variation in $\Delta D_{t-\text{reuse},t-\text{new}}$introduces substantial variability in the outcomes, underlining their critical role in identifying the minimum cutting size.

Cutting Tool Performance Variation: Another crucial factor is the cutting tool's performance, depicted by the purple area in figure 4. Compared with other similar tools available on the market, the DST20-CA wall saw is the best available technology, boasting exceptionally high cutting speeds. It is important to note that not all sites conducting concrete reuse employ the same tools or operate at the same fast cutting speed. The variations in cutting speed primarily arise from various factors. Such as the hardness of aggregates, the presence of more rebars, or the wall saw machine used, as observed from onsite data and interviews. Therefore, to address the impact of speed variation on the minimum cutting length, we assumed the use of the same power tool as the HILTI DST20-CA. This assumption ensures that the energy-related unit GHG emissions remain constant, focusing on how the cutting speed influences the final results. Variations in cutting speeds result in longer cutting times, consequently leading to increased energy consumption associated with cutting.

As a result, the minimum cutting size, which also represents the threshold for sustainable practice, differs significantly. Older models of cutting wall saws consume more energy and generate higher emissions, rendering reuse less sustainable and demanding stricter cutting thresholds.

These differences emphasize the significance of using modern, efficient cutting tools. Customizable calculation tools will allow users to compare performance to benchmark results and advocate for more sustainable reuse practices.

GHG Emissions due to Energy Source Variation: The prior sections were based on using a diesel generator, which offers flexibility for sites without grid electricity. However, the HILTI DST20-CA also supports grid electricity as its primary energy source for cutting, eliminating the need for a generator when grid power is available. We applied the same analysis to assess the impact of using grid electricity versus a diesel generator for reducing GHG emissions. The results, indicated by the green area in figure 4, show that utilizing grid electricity for concrete reuse consistently results in lower GHG emissions than using a diesel generator, mainly due to higher GHG emissions from diesel operation.

In our Swiss case study, the carbon intensity of grid electricity is notably low, primarily due to the predominance of nuclear and hydroelectric power, although this might not be the case in other countries. On a global scale, for the 168 countries surveyed with data from Ecoinvent 3.10, GHG emissions from electricity vary significantly, ranging from 0.0023 $\text{kgCO}_2 - \text{eq/kWh}$ to 1.6 $\text{kgCO}_2 - \text{eq/kWh}$. The analysis revealed that variations in the minimum cutting size due to the energy source are minimal because high-speed cutting has a negligible impact on energy consumption. However, reducing the minimum cutting size still underscores the importance of selecting cleaner energy sources for cutting processes to minimize emissions.

The detailed assumptions and corresponding results are summarized in table 2, where a diesel generator is used except for the energy source variation scenario, where grid electricity is used. This demonstrates that the most significant variation and increase in the minimum cutting length result from imperfect tool performance and low cutting speeds. These observations emphasize the importance of transportation, cutting tool performance, and energy sources in determining the sustainability of concrete reuse practices.

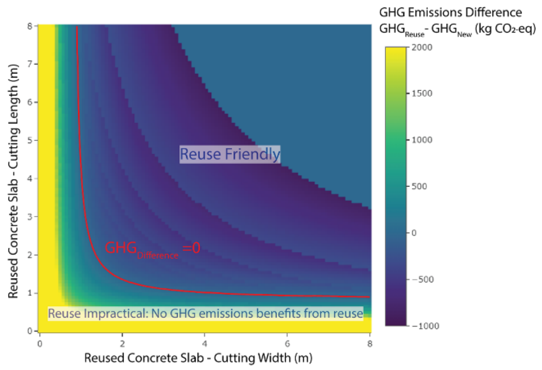

Figure 5. GHG emissions difference ($GHG_{reuse} - GHG_{new}$) of reused concrete slabs of various sizes, assuming equal transportation distances of 100 km.

3.3. Reused concrete slab

In contrast to concrete beams, concrete slabs typically feature a lower reinforcement ratio. For instance, a 1% reinforced slab utilizing lightweight aggregates generally produces lower GHG emissions during manufacturing than does a beam of the same volume. Additionally, the reduced rebar content can slightly increase the cutting speed for reuse, further lowering the emissions associated with the cutting process. By treating both the height and width of the cut pieces as variables, following the same mathematical model development, we generate a visualization of the relationship between the cutting area and GHG emission differences for a 0.2 m thick concrete slab, as demonstrated in figure 5. For simplicity, our analysis isolates the effect of cutting size while holding other factors constant, such as a 100 km transportation distance for both scenarios, cutting performance using the DST20-CA wall saw, and a diesel generator as the energy source. The colour bar on the right side of the plot shows the difference in GHG emissions. Yellow and green indicate greater differences in GHG emissions (i.e. greater GHG emissions from reusing the slab than from using a new slab), while blue and purple indicate greater GHG savings from reuse. The zero-impact-difference line represents the boundary where GHG emissions from reused and new slabs are equal. To the right and above this line ('Reuse Friendly'), reuse results in lower GHG emissions. To the left and below this line ('Reuse Impractical'), reuse does not offer GHG benefits. This identifies the size range of the cut concrete slab that qualifies for effective reuse. The 'Reuse Friendly' area indicates that larger cutting dimensions lead to GHG savings, while the 'Reuse Impractical' area suggests that smaller dimensions are less efficient due to higher processing and transportation emissions. When evaluating a 2 m × 2 m slab, the GHG emissions evaluated by the model for reused concrete (1205.52 $kgCO_2 - eq$) are significantly lower than those for new concrete (1445.50 $kgCO_2 - eq$). This results in a net savings of 239.98 $kgCO_2 - eq$, demonstrating the environmental advantage of reusing larger slabs. In contrast, for a 1.5 m × 1.5 m slab, the GHG emissions for reused concrete (1590.23 $kgCO_2 - eq$) exceed those for new concrete (1490.67 $kgCO_2 - eq$) by approximately 99.56 $kgCO_2 - eq$. This represents a 32% increase in GHG emissions compared to cutting larger slabs. This implies that reusing larger slabs is more environmentally beneficial, emphasizing the need to evaluate both cutting length and width to maximize GHG emissions savings.

4. Discussion

Our study examined the GHG emissions of reusing concrete in construction compared to the traditional approach of producing and transporting new concrete. By analysing the GHG emissions associated with preparing reused concrete, we found that concrete reuse could offer significant environmental advantages as long as it is carefully considered. Specifically, the extent of these environmental benefits varies based on several factors, including the cutting size, transportation distance, cutting tool efficiency, and energy consumption rate of the cutting equipment. For instance, in terms of cutting size, for a 0.4 m × 0.4 m reinforced concrete beam transported at 100 km, reducing the cutting size from 0.35 m to 0.25 m not only alters the scenario of reuse benefit but also increases GHG emissions by 35%. For a 0.2 m thick slab at the same transport distance, a 2 m × 2 m cut could reduce GHG emissions by more than 32% compared to a 1.5 m × 1.5 m cut.

Previous studies have also highlighted the environmental advantages of concrete reuse [8, 12]. However, our study contributes to the literature by providing a quantitative assessment model of the minimum cutting size that offers the best environmental outcomes. The general benefits of reusing concrete components were carefully discussed, but no specific thresholds for cutting sizes were established to offer clear guidance on the cutting dimensions for reuse.

The concept of minimum cutting size is pivotal in evaluating the GHG emissions of concrete reuse strategies and serves as a critical benchmark for decision-making. The minimum cutting length for reused concrete is influenced by various factors. Our study critically examines the impact of transportation distances, showing that longer distances between the demolition site and the construction site can reduce the environmental benefits of concrete reuse due to increased GHG emissions from transportation. This finding aligns with the principles of the circular economy and the waste hierarchy framework [10, 19], which emphasize the importance of reducing transportation distances to enhance sustainability. Moreover, the efficiency of cutting tools and the energy consumption rates of cutting equipment are critical factors that determine the minimum cutting size. The use of modern, efficient tools, such as the DST 20-CA wall saw used in our study, can reduce energy consumption during the cutting process, thus minimizing the environmental impact. This aligns with the findings of past studies that have examined the role of technology in sustainable construction practices [26, 27].

Recognizing these factors enables stakeholders to make informed decisions about concrete reuse strategies, optimize cutting methods and select efficient transport methods, thereby reducing GHG emissions. This approach not only promotes environmental preservation but also advances sustainable construction practices within the industry.

However, our research has limitations, including the exclusion of energy consumed by cranes or in the mixing of new concrete, which, although minor, requires further data to be accurate. Various factors, such as the quality of concrete, project-specific requirements and cutting methods, as well as real-world transport inefficiencies, such as empty return trips, were not fully considered but can be incorporated into a future version of the developed model. While this study focuses on the environmental aspects of concrete reuse, future research will explore cost effectiveness and field case studies to validate our findings and illustrate the GHG reduction potential of sustainable construction practices.

5. Conclusion

The idea behind this study originated from a fundamental question: Is it always worthwhile to reuse concrete in construction? Our primary aim was to provide a grounded answer supported by robust evidence and quantitative evaluation, showing that concrete reuse is not a mere fairiary concept limited to specific conditions. Instead, we demonstrated that concrete reuse is a practical and effective strategy, given that we carefully address the relevant constraints.

Our findings reveal the GHG emissions involved in cutting and transporting reused concrete versus producing new concrete, leading to the identification of a minimum cutting size threshold. This study provides a critical analysis of the environmental benefits of concrete reuse and identifies the factors that influence the minimum cutting length for optimal GHG emission reductions. This study offers practical guidance for the construction industry to lower GHG emissions through concrete reuse, highlighting that the feasibility and environmental advantages of concrete reuse promote waste reduction, resource efficiency, and a circular economy. Our recommendations aim to encourage broader adoption of concrete reuse, contributing to a more sustainable and eco-conscious construction sector.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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valuable references enriched our study and advanced our understanding of concrete reuse and sustainable construction practices, which enabled the development of the tool prototype, available for public access at [Circular Future Cities - Work Package 2].

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