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Design-Stage Carbon Reduction Pathways for Steel Structures

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Abstract

Steel framing is a predominant system used in buildings and is common for large scale structures and tall buildings. Despite the widespread recycling of steel, new steel structures have large carbon impacts, which can be dramatically reduced by reusing steel. There are significant challenges to designing buildings that enable reuse of components, as well as with current estimation methods used in Life Cycle Analysis. Inspired by real building projects, this paper executes a workflow for assessing carbon savings for several strategies including span reduction and reuse. Using both real-world case study buildings with dimensioned steel framing plans and generative models with different spans, the research demonstrates the potential of different reuse scenarios and the design implications of introducing material reduction strategies at the building scale – ultimately proposing steel structures that can maximize their reuse potential while enabling lower material use through detailed analysis.

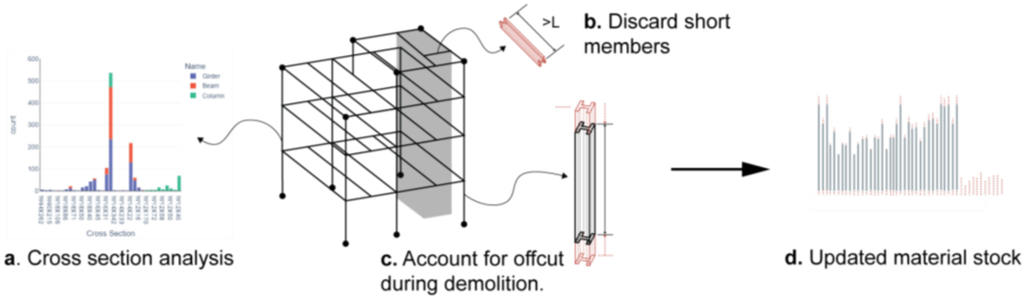
Keywords: geometric optimization, reuse, steel structures, life cycle analysis, sustainable design strategies

1. Introduction

The construction industry is the most dominant demand sector globally for steel products, and contributes to 25% of global industrial emissions [1]. Demand for steel is anticipated to increase through 2050 [1], and considering the urgent need to reduce carbon emissions of the built environment, there is a necessity to employ sustainable methods in new buildings. Life Cycle Assessments (LCA) are often done after a structure is already designed. However, to lower embodied carbon, proactive measures can guide early stage design [2]. In the hierarchy of sustainable design pathways for the built environment, four carbon-reduction strategies have emerged to reduce embodied carbon in buildings: building nothing, building less, building clever, and building efficiently [3]. While researchers have identified sustainable design strategies [4], [5] and comparative analyses have contrasted material efficiency and low carbon building materials [6], as well as reuse of a specific material stock into standard frame structures [7], more research to quantify the potential carbon-reduction of a combination of methods for steel structures is needed.

Geometry of structural elements are key for addressing reuse potential of steel framed structures [8]. Expanding on methods that utilize generative structural geometry to assess a building's embodied carbon [9], this paper demonstrates how geometric structural models can be used to assess a building’s savings potential from reuse, and through that, more accurately predict carbon emissions of the steel structure over its life cycle.

This geometry-informed workflow for assessing reuse, as illustrated in Figure 1, utilizes a dimensioned structural model of a building’s steel frame. The structural model acts as a framing plan of an existing structure, as well as a virtual generative model of a building's proposed structure. In this research, the geometry and cross sections of the steel frames of five buildings were annotated and digitized. This data is used to validate a virtual generative multi-story structural model of two of the buildings. Both the real-world dataset as well as the generative models can then be used to assess the impact of design stage carbon reduction strategies and their relationship to reuse. This allows a comparison of the impact of reductions of span and compares them with different reuse scenarios. A cut-off method LCA is then carried out to determine potential carbon savings from reuse, followed by an exploratory analysis varying the structural layout. The research shows how LCA comparisons for reused steel [10] can be combined with geometric models to guide designers to structural solutions that can further reduce material use and increase material reuse.



a. Cross section analysis

b. Discard short members

c. Account for offcut during demolition.

d. Updated material stock

Figure 1: Geometry informed reuse analysis of steel structures.

2. Literature Review

Most research has focused on sustainable design strategies for steel structures in the material processing LCA stages. Efforts to advance steel recycling through the robust use of Electric Arc Furnaces (EAF) have reduced the energy intensity of new steel, but current best steel making processes are not enough to meet IPCC goals alone [11]. A wide variety of design strategies can be implemented to lower the embodied carbon of a building, however their impact is difficult to quantify, where different strategies are focused on material or system selection [5]. For steel, reuse has been identified as a sustainable design strategy [12], circumventing the carbon impacts due to steel production processes [13] and allowing for an extended life cycle of building elements. Steel cross sections are tailored and dimensioned for each building individually. While it has been shown that with minimal structural weight tradeoffs, the number of cross sections used can be reduced significantly [14], further research must address the carbon impact of standardization at urban scale, weighing the potential of span length and reuse of structural elements.

2.2 Generative design for structural modeling

In order to understand the environmental impact of a building, it is necessary to accurately understand material quantities[15]. A building model further enables impact assessment, because building characteristics that contribute to impacts, such as including height and section type, can be measured. Prototypical and idealized buildings have been used to assess early-stage design decisions and highlight the importance of material and design choices on the carbon emissions of buildings. Generative models that approximate real-world buildings have been used to benchmark embodied carbon emissions by creating structural models of single floors [9]. Simplified building models with artificial geometries have further been used to study cost, embodied, as well as operational emissions [16], [17]. While different material systems can be combined [18], this research focuses only on steel structures.

2.3 Reuse scenarios in literature

Several papers analyze reuse through specific case studies of structural systems including portal frames for industrial buildings [19], [20], reticular structures [21], steel frame buildings [22], and generic structures at the end of its service [23]. Literature provides carbon equivalent savings potential for specific functional units, primarily in 1 kg of steel [21], [22], [24]. This paper utilizes an early iteration of the methodology from Berglund-Brown [24] to understand the global warming potential of reused steel framing in kgCo2e per area of building projects. Factors impacting reusability, reuse rate, and impact of offcut waste has been analyzed [21], [25], but not for different reuse scenarios developed through industry precedent.

3. Methods

3.1. Building Dataset Synthesis and Digitization

The analyses carried out in this paper are highly dependent on utilization of real building data, including building typology, geometry, framing layouts, floor heights, and section information. For this, real world buildings (originally used in [10] and [26]) from the Steel Solutions Center at the American Institute for Steel Construction, were used. After a preliminary assessment to qualitatively determine data relevance and quality, five steel framed buildings were selected for analysis in this study (Figure 2). Some building characteristic information can be found in Table 1. For this analysis, only the steel gravity systems were analyzed for reuse and optimization.

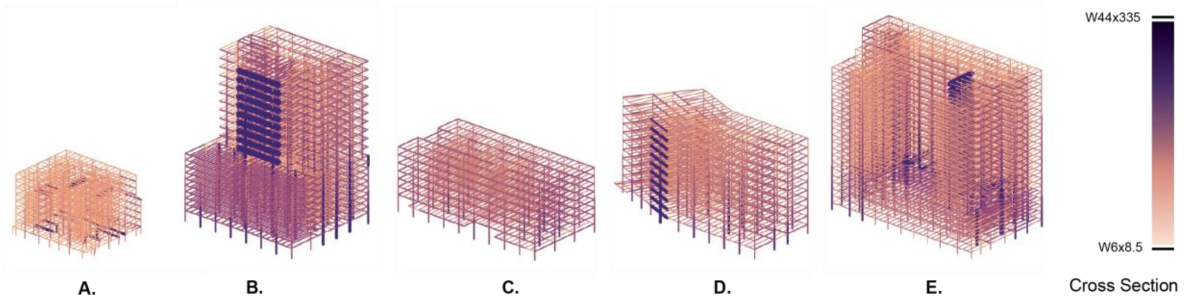


Figure 2: Comparing measured data of the cross sections of the 5 different real-world buildings.

Table 1: Building Data Characteristics

Project Location	Project Id	Use Type	Area (m^2)	Building Height (m)	Floors Above Grade	Floor to Floor Typical (m)	SW (t)	Number of Beams	Number of Columns
Denver, CO, USA	A	Residential	11903	58	8	3.3	462	1102	268
Raleigh, NC, USA	B	Parking & Office	57150	81	22	4.2	2934	2572	355
Baltimore, MD, USA	C	Mixed Use	33057	37	8	3.9	1227	1232	158
Denver, CO, USA	D	Office	33404	92	15	4.2	1256	1349	198
Dallas, TX, USA	E	Parking & Residential	68765	74	22	3.3	2390	3385	515

3.1.2. Digitization workflow

Dimensioned framing plans of beams, girders and columns were used to create a digital version of the steel framed structure. The digitized plans have attributed cross sections and member lengths of each element in the structure. The plans were annotated and digitized inside Grasshopper and Rhinoceros 3D, a parametric modeling environment and CAD software [27]. To make the buildings comparable, basement parking floors were omitted and only floors above grade were considered to comprise the steel framed gravity system.

3.2. Life Cycle Assessment for Reuse

The life cycle impacts of a reused element vary across the number of life cycles considered, allocation of impacts, etc., and therefore many methods exist for LCA of reused elements [28]. This analysis employs the cut-off method wherein all production impacts fall into the first use cycle. This paper follows the Life Cycle Assessment (LCA) methodology in early development in [26]. All relevant assumptions and processes are stated below, however additional information about how the LCA was performed can be found in [10] and [26], and is expanded upon to account for additional element characteristics in [24].

3.2.1 Boundary conditions, processes, and assumptions

The boundary conditions in this analysis are demonstrated in Figure 3. This analysis includes raw material supply, transport, and manufacturing, which make up modules A1- A3 impacts in the BS EN 15978 standard [29]. The primary differentiator between business as usual and reused elements is module A1, where, for reused elements, raw material supply consists of deconstruction and refurbishment processes for salvaged steel. The processes analyzed are cutting, hoisting, and grinding. Transportation is assumed to be the same across all building scenarios for comparability and is assumed to be 400 kilometers. Manufacturing is also assumed to be the same across all building scenarios and considers fabrication as the primary manufacturing process. This section utilizes guidance from the Carbon Leadership Forum (CLF) for fabrication and business as usual assessments [30].

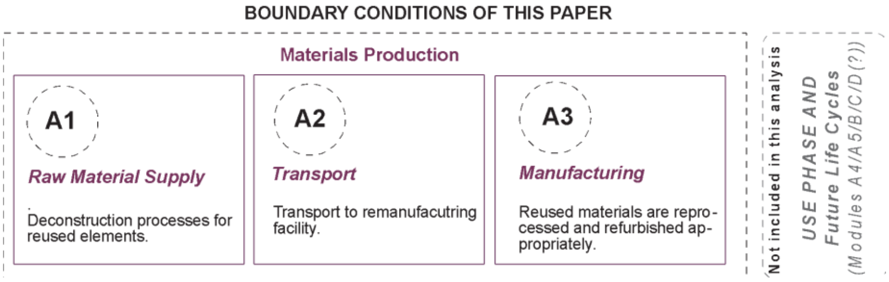


Figure 3: Boundary conditions

3.2.2 Scenario development

One business-as-usual, and three reuse scenarios were developed based on the existing building data for this analysis. The business-as-usual scenario assumed new steel was produced in an Electric Arc Furnace (EAF), and that 85% of inputs to the EAF was scrap. The first reuse scenario assumed 100% of elements were reused. The second assumed 0.3 meters of each beam was cut-off at each end of the beam, and each off-cut was melted down in an EAF. The third scenario assumes all beams shorter than 4.57 meters were not reused, and were instead melted down. The impacts of melting off-cuts and non-reused beams were considered in the A1 impacts for reuse. The criteria for scenario one and two were determined through an industry interview with an engineer on a notable deconstruction and reuse project [31].

3.1.1. Business as usual

The business-as-usual approach was carried out as a baseline to compare carbon reduction strategies against and is calculated by adding A1 impacts for recycled steel, to A2 and A3 impacts. A1 impacts for recycled steel are estimated using the CLF baseline Global Warming Potential (GWP) values in kg CO2e/kg hot rolled section steel. The CLF baseline is obtained from an environmental product declaration produced by the American Institute for Steel Construction [32]. Equation 1 demonstrates the baseline calculation where w_p is the weight of the project and A_p is the area of the project. All three scenarios calculate A2 and A3 impacts using the same approach, by using the GreenHouse Gas Protocol for transportation (E_t) [33], and the CLF baseline for fabrication calculations (E_f).

$$GWP\left(\frac{kgCO2e}{m^2}\right)=\frac{(1.08*w_p)+E_t+E_f}{A_p} \quad (1)$$

3.1.2. Reference + reuse

The reference + reuse project is the least conservative scenario and assumes all elements in the building are reused. The emissions associated with reuse are first considered, using an emission factor for hoisting (EF_h) assuming one hoist per element, cutting (EF_c), and grinding (EF_g) established in a preliminary iteration of the methodology in [24] along with number of cuts (n_c) and area of grinder (a_g), h, d_e, a_e are all dependent on each element, and refer to height of element, depth of element, and area of element respectively. Further iterations also consider element thickness, but not the methodology in this analysis. E_R in Equation 2 represents A1 for the reference and reuse scenario.

$$E_R = \sum_{i=1}^{n}((EF_h * h\ ) + (EF_c * d_e * n_c\ ) + \left(EF_g * \frac{a_e}{a_g}\right)) \qquad (2)$$

$$GWP\ \left(\frac{kgCO2e}{m^2}\right) = \frac{E_R + E_t + E_f}{A_p} \qquad (3)$$

3.1.2. Offcut and length requirement

Scenario 2 (offcuts) assumes 1 foot at each end of the beam is scrapped and recycled. w_o is the weight of the offcut and added to the reference + reuse scenario equations. The weight of the offcuts is excluded from the calculation of E_R . The GWP is calculated by adding $E_o = (1.08 * w_o)$ to the numerator of equation 5, where w_o is the weight of offcuts.

Scenario 3 (length requirement) assumes all elements that do not meet the aforementioned height criteria are unused and scrapped and the impacts of melting are considered to be a part of production. The GWP is calculated by adding $E_u = (1.08 * w_u)$ to the numerator of equation 5, where w_u is the weight of the unused elements.

3.3. Generative whole building models

The generative model is a physics-based simulation to estimate the material quantities of a building. Using a real building's massing geometry and high-level parameters, such as average span and floor to floor height, a structural model is automatically created. The method expands on existing research [9] where the steel structure of prototypical floor plates of a building is approximated. Here, the whole building volume is divided by a specified floor-to-floor height to create different floor plates that approximate a full structural model of a building. To generate the structural model of the whole building, a rectangular grid is projected and aligned to the longest axis of the ground floor plate with specified spans for the girders. The grid is then projected upwards to each of the subsequent floors, with columns placed at the intersections. In a secondary step the grid is divided in the longest direction of each cell to create the beams. Using the Finite Element Analysis package Karamba3D [34] floors are loaded with 4.2 kN/m2 (for the midrise A.) and 5.7 kN/m2 (for the tower B.) to dimension the gravity system. To simplify the analysis, and to be able to compare the results to the gravity systems of the real-world datasets, no lateral loads are considered. Buildings A. and B. are recreated as generative models with the average and with a 25% span reduction, as compared to their real-world counterparts. The label and length of the dimensioned cross sections are output for analysis.

4. Results

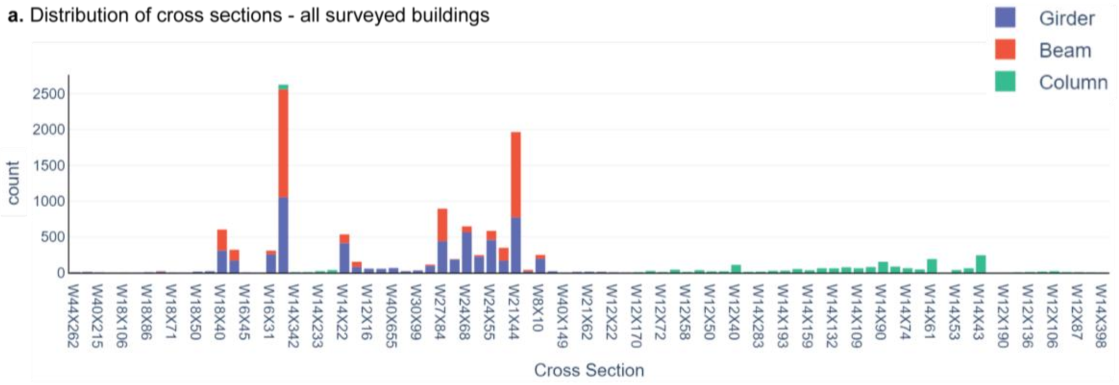
4.1. Real World Buildings

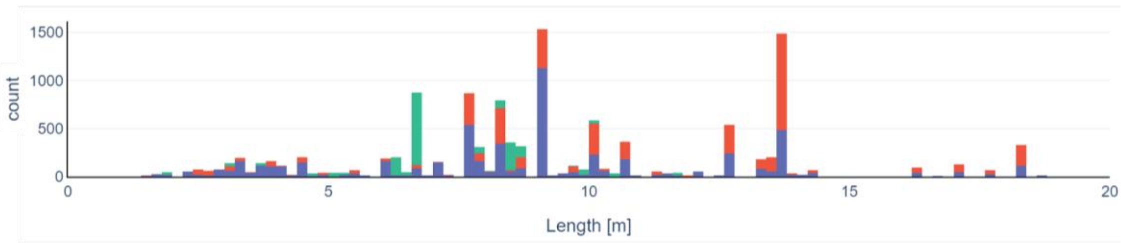
The three new reuse specific LCA scenarios; Reference + Reuse, Offcut, and Length Requirement are compared to a standard business as usual LCA approach (Table 1). The analysis shows that incorporating offcut and length requirements increases the embodied carbon when compared to a standard reference and reuse scenario. Both offcut and length requirements vary similarly across building geometries and typologies.

Table 1: Design Strategy Comparison (in kg Co2e/m^2)

Identifier	**EC BAU**	**Reference + Reuse (RR)**	**Offcut (% to RR)**	**15 feet Length Requirement (% to RR)**
A	48.36	6.82	8.99 (+31.8%)	7.97 (+16.9%)
B	64.23	9.06	11.06 (+22.1%)	9.98 (+10.2%)
C	46.11	6.5	7.85 (+20.8%)	6.76 (+4.0%)
D	50.63	7.14	8.74 (+22.4%)	7.78 (+9.0%)
E	64.41	9.08	11.45 (+26.1%)	9.54 (+5.1%)

We compare the different cross section types, member lengths and cross-sectional areas of the surveyed buildings in Figure 4. The results show how there are a small number of cross sections (>10) used across the different buildings with occurrences of over 250, and a wide range of cross section types that are used sparsely. A relatively wide distribution of member lengths is found. The survey shows how column elements lower in the building have larger cross sections, while beams and girders have cross sectional areas indifferent to location in the structure (as they are dimensioned for spans).


a. Distribution of cross sections - all surveyed buildings


b. Distribution of member length - all surveyed buildings

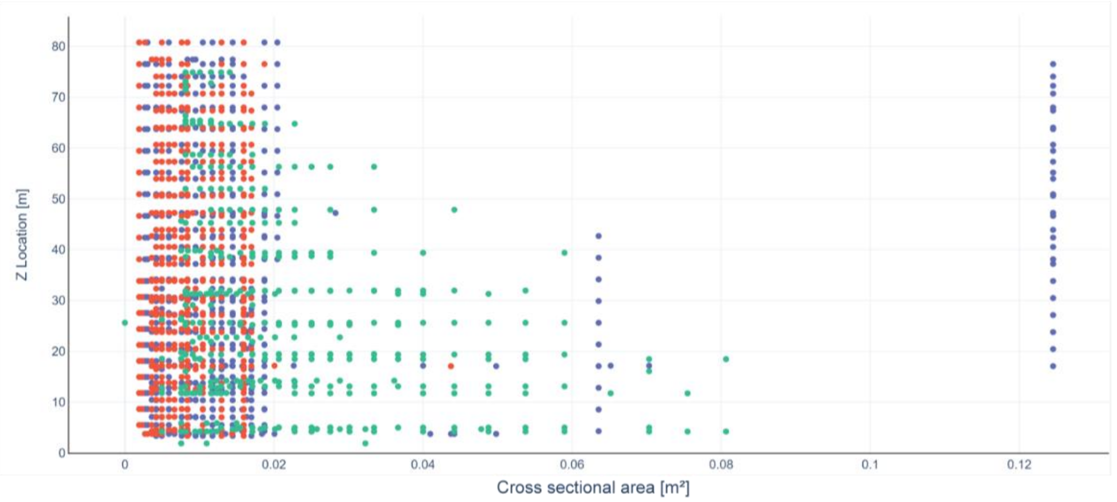

c. Cross sectional area and member location above ground

Figure 4: Aggregated structural elements of the studied real-world buildings.

4.2. Generative model and span reduction

Using the existing buildings with measured material quantities as a validation dataset, the developed generative model was applied to sample building A and B where it could predict structural material quantity within a 10% error margin Figure 3. Buildings A, a mid-rise structure and B, a tower structure are compared using generative geometries to assess the influence of spans on carbon and reuse. The results (Table 2) show how even though a reduction in length might be beneficial from an initial carbon standpoint before construction, in both of the simulated buildings, the reduced length strategies could have a negative effect on the savings from buildings reuse, considering the greater number of long elements limit the number of unused elements.

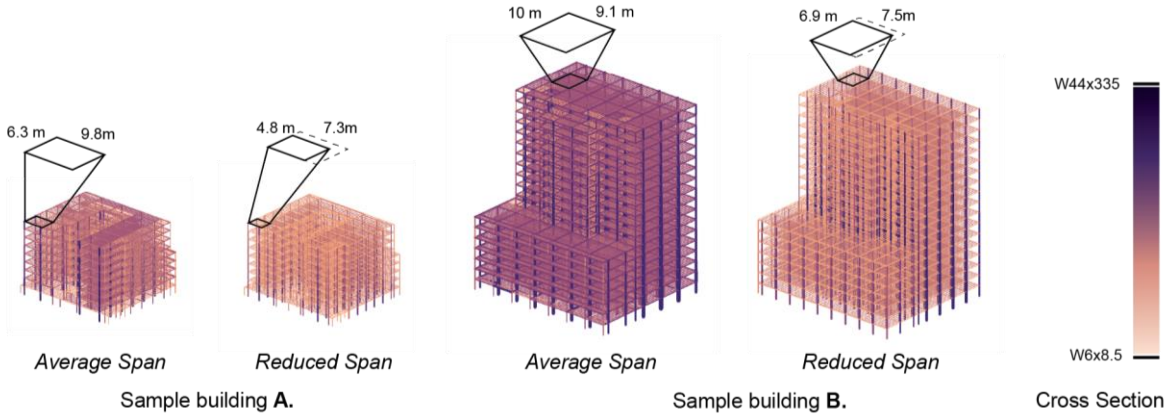


Figure 5: Comparing steel cross sections of generative models of A and B with average, and reduced spans.

Table 2: Combined Design Strategies (in kgCo2e/m^2)

Number	Name	EC BAU	Reference + Reuse (RR)	Offcut (% to RR)	Length Requirement (% to RR)
A	Generative	50.35	8.32	10.46 (+25.7%)	12.47 (+49.9%)
A	Reduce Span 1 (x and y)	39.12	6.7	8.71 (+30.0%)	11.07 (+65.2%)
B	Generative	65.78	10.33	12.78 (+23.7%)	18.44 (+78.5%)
B	Reduce Span 1 (x and y)	48.06	7.81	9.96 (+25.7%)	15.82 (+102.6%)

5. Conclusion

Early understanding of the embodied carbon of steel structures and the impact of design decisions on potential reuse of buildings is crucial for the design of more sustainable buildings. While reusing building elements proves beneficial in hypothetical reuse scenarios, more detailed strategies that include measurement from real life demolition scenarios is needed. Demolition protocols could inform not only the creation of new buildings but would ensure more accurate LCAs and embodied carbon benchmarking of reused buildings for future construction; reduce uncertainties and margins of error. This analysis found significant differences in the simple reference + reuse analysis, when compared with more detailed geometry informed reuse LCA that includes offcuts and length requirements. This suggests more detailed calibration of actual demolition practices with embodied carbon benchmarks are needed.

Real world building datasets are an important tool for benchmarking digital models, as they provide a framework to calibrate virtual design strategies. The research highlights the importance of building typology and design, such as geometry or spans, or demolition strategies. In the case of the surveyed buildings, increasing the height of a building from a midrise (8-story) to a tower (22-story) meant an increase of almost 30% in embodied carbon per square meter, highlighting how building typology is critical when it comes to carbon emissions of a building.

Furthermore, this paper demonstrates how a geometry level analysis can reveal opportunities and drawbacks of different designs when coupled with demolition informed offcut and length requirements.

This highlights how generative design in tandem with environmental impact assessment can be an important tool not only for estimating material quantities but also for tailoring a structural geometry to reuse.

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