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Calculating embodied carbon for reused structural components with laser scanning

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ABSTRACT: The global warming potential (GWP) of reused building elements can be evaluated based on two variables: structural material quantity (SMQ) and embodied carbon coefficient (ECC). The volume of the SMQ can often be unknown, however, and it is not clear how to best estimate the ECC of a reused element. This paper illustrates a method for extracting the volume of reused metal structural elements to calculate their GWP in buildings that lack documentation. The authors use laser scanning and voxelization to extract the volume and a method based on the Swiss Society of Engineers and Architects (SIA) 2032 norms for calculating the GWP of reused materials. The reality capture method is accurate enough to approximate structural material volume, although it requires exposed structures. The results are important for building managers to understand the relative environmental impact savings from reused versus new building elements.

1 INTRODUCTION

New structural design methods are needed to achieve many industrial and governmental goals for sustainable construction. In the closed material system of planet Earth, it is imperative to be more efficient with building resources and to understand how to use what is already available. Circular construction and the reuse of building elements is a growing approach for minimizing environmental impacts through lowering embodied emissions in the product stage of the construction process. One approach for measuring embodied emissions is through measuring global warming potential (GWP), a sub-factor of a traditional life cycle assessment. There are existing methods for measuring GWP in new projects but measuring GWP in the current building stock is limited due to a dearth of as-built drawings and further information on existing building stock. Two challenges prevent understanding of how reused building components affect the net environmental impact: no consensus on a method currently exists for calculating the GWP of reused components, and documentation is usually lacking the volume and material data of existing components in buildings. From these issues, the research question arises: how can we extract the estimated volume of metal structural elements to calculate their GWP in buildings with no documentation?

1.1 *Review: Reality capture for reuse and volume estimation*

Reality capture technologies, such as Lidar laser scanning and photogrammetry (photographic image analysis), are increasingly used in the architecture, engineering, and construction industry for applications such as construction progress monitoring (Dimitrov and Golparvar-Fard 2014, Bosché *et al.* 2015), continuous site inspection (Hutter *et al.* 2018), interior mapping (Tchapmi *et al.* 2017), and scan-to-BIM (Pătrăucean *et al.* 2015, Iglesias *et al.* 2019). Although work is emerging on reality capture for circular construction (Xiong *et al.* 2022), building component volume estimation has yet to be thoroughly explored (Xu *et al.* 2021).

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A common volumetric application of Lidar is for estimating volume change over time in planar surfaces by integrating point-to-point distances (Puente *et al.* 2013). Similar bulk volume estimation, such as for stockpiles or excavation, is built from the summation or integration of a resulting digital surface model (Manish *et al.* 2022). For geometries with clear axes, volumes are estimated through a series of slices and profiles along their length (Chang *et al.* 2017, Terryn *et al.* 2022). For more complex geometries, volumes are read from an intermediate mesh, generated, for example, by Delauney triangulation (Zhang and Yang 2019), convex hulls and alpha shapes (Terryn *et al.* 2022), or Poisson surface reconstruction (Ma *et al.* 2020). Voxel-based (volumetric cubic grid) approaches have been applied in domains with irregular density complexity (Kim *et al.* 2016). Finally, additional domain information may be integrated, such as by combining surface segmentation with associated material volumes for typical building typologies, such as the depth of different materials in walls (Heisel *et al.* 2022). Due to the difficult geometry of the web and flanges of structural metal, a voxel-based approach is best suited and explored in this paper.

1.2 *Review: Calculating embodied carbon of reused components*

One output from the life cycle assessment of structures is the GWP, measured in carbon dioxide equivalent emissions (CO_2-eq). Embodied carbon is the sum of greenhouse gas emissions released outside of the operation stage. It is used interchangeably with GWP in this paper, as both measure the relative impact of a given greenhouse gas on global warming. Existing research has explored how to measure the embodied carbon values of specific building structures to aid early design-stage decisions (De Wolf *et al.* 2014, Iuorio *et al.* 2015). An exposition of relative environmental savings in reusing steel elements demonstrates environmental savings and the relatively low impact of transportation (Brütting, Vandervaeren, *et al.* 2020). A consensus is lacking, however, on how to best calculate and compare the environmental impact of reused building elements (Hoxha and Fivet 2018, De Wolf *et al.* 2020).

This research focuses on the reuse of structural metal components due to the existing research precedent, modularity, and ease of disassembly. Although structural steel typically consists of a very high amount of recycled content (Iuorio *et al.* 2019), there are continuing efforts to focus on component reuse to remove the added energy demands of melting and recasting. Validation of the process of reusing steel components can be found in various case study analyses (Pongiglione and Calderini 2014, Drewniok *et al.* 2017).

1.3 *The contributions of the work*

How to best assess environmental impact for reused building elements is not agreed upon, but reusing structural building elements has undoubted environmental benefits. This research aims to use Lidar scanning to collect data for estimating volume and GWP savings of in-situ reused structural elements relative to new elements. As mesh-based analysis methods have low accuracy and would be difficult to use for this domain, a voxel-based volume estimation method is explored, compared to ground truth volumes, and after testing on a site with known structural volumes applied to a more difficult site. The results of this research will contribute to a growing body of knowledge on the relative environmental impacts of reusing steel building components as well as how component volume calculations can be supplemented with laser scanning.

2 CASE STUDY DESCRIPTION

This research examines two different structures of reused structural elements, the first being a recent steel construction with known structural volumes used as a baseline for the volume estimation techniques. The Kopfbau Halle 118 building (K118) is a building expansion project in Winterthur, Switzerland completed in 2021 under the architecture firm Baubüro in situ AG. Reusing structural and facade materials in the expansion reduced the carbon footprint from construction by around 60%. K118 uses a standard steel girder system with a maximum span of 8.5 m, 1.4 m on center, and a total floor plan area of 230.4 m^2. Prior work in (Brütting, Senatore, *et al.* 2020) looked into the design process using the same stock of steel elements used in K118.

The second structure is in the Grand Café Horta in Antwerp, Belgium, which includes a unique iron portal frame structure in art nouveau style. The café's Art Nouveau Room contains nine cast iron portal frames of differing heights and degrees of completeness, and three half-portals originally designed by the architect Victor Horta from 1895–1899 for the Maison de Peuple. Documentation of the frame is limited. The original Maison du Peuple was deconstructed in 1965, and the trusses were eventually reused in the construction of the Art Nouveau Room in 2000. The current structure is 46.1 m long, 16.3 m wide, and 10.5 m high. Each truss is an open web non-continuous portal frame, spaced 5.2 meters apart. Although the design styles and materials differ, these buildings were chosen because they both had exposed frames of reused structural metal and the developed method can be used on both to explore GWP.

3 METHODOLOGY

3.1 *Data collection and processing*

The volume estimation strategy of structural metal for the embodied carbon calculation employed here covers three main steps. First, raw point cloud data is collected using terrestrial Lidar scanners. This data is then classified and segmented to separate only the points representing the metal structure. Automated segmentation was considered outside this study's scope; the clouds were manually segmented to correspond to the best possible output from automated segmentation. Lastly, the subset of the cloud is geometrically analyzed to produce the final volume estimation

3.1.1 *Approach for K118*

One floor of the K118 building was selected as the test site, wherein most of the steel structure was left exposed with relatively little interior clutter (Figure 1). Scanning was conducted using a Leica RTC360 Lidar scanner. 24 captures were taken over two hours, with a total raw cloud size of 102 million points. The manufacturer software Leica Cyclone was used for registration. Reflection noise was cleaned by manual cropping, and no downsampling was performed as it may have induced aliasing errors with the voxel analysis strategy. The cloud was manually segmented to produce a test cloud containing only the steel points, resulting in 10 million points for analysis (Figure 1). The ground truth steel volume was derived from the original construction drawings, extracted from a model produced with Revit.

Figure 1. Interior view (left) and captured point cloud (right) for K118 (edited for steel visibility).

3.1.2 *Approach for Café Horta*

The Art Nouveau Room was captured using a RIEGL VZ-400i terrestrial laser scanner. The space was captured across 32 scans in two hours, producing a raw point cloud of 580 million points. The manufacturer software RiSCAN Pro 2.0 was used for registration. The cloud was manually cleaned and segmented to retain the iron portals. This site contained more prevalent occlusions both at the bases of the trusses and near the ceiling, which the estimation method does not attempt to account for. This resulted in a cloud of 39.9 million points for analysis (Figure 2).

There was significantly less accessible documentation for this site than for K118. The baseline 3D model was instead based on existing historic modeling work drawing on a combination of

Figure 2. Café Horta, interior view (left), captured point cloud after steel segmentation (right).

archival documentation and on-site photogrammetry (Van Laere 2003, Vaeck 2006, De Prins 2016). Typical details were then adapted to the changes in base height along the length of the site.

3.2 *Point cloud volume extraction*

Given the concave complexity and prevalence of self-occlusions in metal structural geometry, the visible points were directly measured using a voxelization method. Herein, the total space was divided into equal cubic volumes, which were considered filled if they contained any scanned points. The sum of these volumes was considered the raw volume value. The point clouds were pre-rotated to align the major walls to the world axes to reduce aliasing errors. The size of the voxel grid is critical to this estimation, and a range of possible sizes was evaluated between 1 mm and 100 mm. As the ideal size was found to correlate closely with the average web and flange thickness, a heuristic was determined wherein the operator would manually measure a typical element as input. Figure 3 demonstrates the influence of voxel size selection. The middle example is similar to the determined voxel sizes used for the test sites.

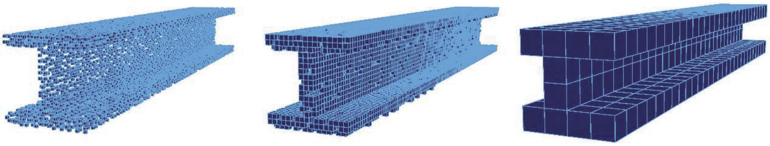

Figure 3. Example beam point cloud voxelization: (left to right) under sized, usefully sized, and oversized.

3.3 *Global warming potential calculations*

Full life cycle assessments are broad in inventory requirements and impact assessment scope, but focusing the assessment to a single impact factor, GWP, increases accessibility for industry to make informed decisions about relative carbon footprint of building materials (Bala *et al.* 2010, De Wolf *et al.* 2014, 2020). Cradle-to-gate GWP of structures can be calculated by multiplying two variables: structural material quantity (SMQ) and embodied carbon coefficients (ECC), as demonstrated in Equation (1) below (De Wolf *et al.* 2014):

$$SMQ\ \left(kg_m/m^2\right) * ECC\ \left(kg_{CO_2e}/kg_m\right) = GWP\ \left(kg_{CO_2e}/m^2\right) \tag{1}$$

SMQ can be calculated from the volume of material, the density of the material, and the floor area of the structural system. The ECCs, in this case, capture only the embodied emissions in the product life cycle stages A1–A3 (SIA 2020). ECCs differ depending on the data source. To stay consistent with the chosen environmental impact method and location for one of the buildings, the ECCs used are from the Swiss KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren) database.

The method for calculating the GWP of reused components is not straightforward. Research done by De Wolf *et al.* (2020) compares six different environmental impact allocation methods for building components reused over *n* life cycles. This paper used one method derived from the Swiss Society of Engineers and Architects (SIA) 2032 norms to demonstrate the GWP reduction associated with reusing building components. The adapted SIA 2032 method compares the total time of use to the time of expected use (design use) as a factor for the ECC. For calculating the environmental allocation of previous life cycle(s), one takes the percentage of actual use over design use. For the current life cycle, if combined actual use has exceeded design use, then the allocation is zero. If combined actual use is less than design use, then the allocation is proportional to the projected remaining years of actual use over design use.

Additionally, using the SIA 2032 norms, all building components have a maximum of 60 years of design use (SIA 2020). This value is arbitrary and may not correspond to actual life cycle but helps normalize comparisons. The first life cycle of the Café Horta structure was in use for 66 years until it was dismantled in 1965. Its second life cycle (in use since 2000) equates to an extra 22 years at the time of this study. The structural steel used in K118 was only in use for 15 years in its first life cycle and has been in use since 2021 for its second life cycle. Therefore, considering a 60-year design life, significant GWP is allocated in the reused K118 building elements due to its very short initial life span.

4 RESULTS

4.1 *Validation of the volume estimation approach*

While testing voxel sizes between 1 mm and 100 mm, 10 mm was found to produce the least error for K118. This roughly correlates with the typical web and flange size on site, matching the chosen heuristic measurement. The density of structural steel is approximately 7850 kg/m^3, thus the total mass of steel reused in the K118 site is approximately 13,229 kg. In the Grand Café Horta site, the best voxel size was found to be 7 mm, likewise in the range of flange sizes present on the site. The best-estimated volume from existing records was calculated at 4.168 m^3, while the best voxel volume estimate was 3.771 m^3. However, the volume from estimated records had lower confidence due to less documentation. Table 1 shows a summary of the volume values extracted from documentation of both buildings compared to the estimated volume from the scanning method, plus a percentage error.

Table 1. Comparison of estimated and calculated structural metal volume.

	Raw Point Count	Segmented Point Count	Volume from Documentation	Volume from Scan	Volume Error
Project	millions	millions	m^3	m^3	%
K118	102	10.2	1.698470	1.685224	0.78
Café Horta	580	39.9	4.168164	3.771370	9.51

4.2 *Results from GWP analysis*

4.2.1 *SMQ calculation*

For the structural material quantities, information had to be collected not only on the total volume of the structural metals but also on the floor plan area and material density. The floor

Table 2. Structural material quantities per project.

			Material Density	Total Volume	Floor Plan	SMQ
Project	Location	Structural Material	kg/m^3	m^3	m^2	kg/m^2
K118	Switzerland	Steel	7850	1.69847	230.4	57.87
Café Horta	Belgium	Cast Iron	7300	4.16816	751.4	40.49

plans from the architects of K118 and some general information on the Café Horta building were used to calculate the floorplan. The results can be seen in Table 2 below:

4.2.2 *GWP results for new material verse reused*

Following Equation 1, the GWP of the structures assuming new material was used and calculated by multiplying the ECC and SMQ of the materials. The ECC values used for the GWP calculation are drawn from the 2022 life cycle assessment data published by KBOB. The product stage emissions for steel profiles are 0.731 kg CO_2-eq/kg_m, and the product stage emissions for cast iron are 2.1 kg CO_2-eq/kg_m. Note the emissions for cast iron are based off current production values, likely, the impact from the original manufacturing at the end of the 18th century would be worse. The resulting GWP calculations for the structural systems assuming new components were used are reported below in Figure 4. The GWP values assuming new building components are 42.30 kg CO_2-eq/m^2 for K118 and 85.04 kg CO_2-eq/m^2 for Café Horta. Figure 4 shows the calculated GWP of the actual structures with reused components with the method adapted from SIA 2032. The GWP values of the actual reused building components are 31.73 kg CO_2-eq/m^2 for K118 and 0.00 kg CO_2-eq/m^2 for Café Horta. Reusing elements reduces GWP by 25% and 100% for K118 and Café Horta, respectively.

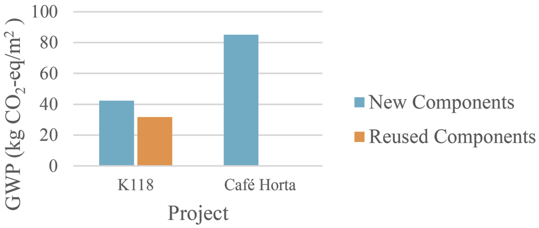

Figure 4. Global warming potential for new and reused components per project.

5 DISCUSSION

The estimation method achieves good accuracy in a setting with strong point coverage on all surfaces for K118. The voxel method's reliance on visible areas and lack of extrapolation necessitates taking many scans on site to avoid high occlusion scenes. While the method would not be strongly affected by small amounts of noise in the segmentation, consistent confusion by the model would quickly compound across the entire cloud. The effects of high occlusion were evident in the higher error for Café Horta, and the unseen points are consistent with the volume underestimation, which probably contributed to the 9.51% error. Additionally, though the chosen 7 mm voxel size falls within the set of flange sizes for this site, increasing component variation typically necessitates increasingly frequent spot checks for verification.

The design specifics also affect the necessity of the method. While a single-story space with standard components such as K118 could be measured and calculated manually, structures with significant height and complexity would be less tenable and benefit more from automation.

A thorough embodied carbon analysis of reused building elements should account for other stages in the life cycle. Hidden carbon costs include intermediate transportation and potential remanufacturing, which are neglected when using the SIA 2032 method for reuse. However, research demonstrates transportation has a relatively low impact on the total embodied carbon of building components (Seo *et al.* 2015, De Wolf *et al.* 2018, Brütting, Vandervaeren, *et al.* 2020).

The use of the adapted SIA 2032 method prioritizes reusing building components that have already served longer lifespans: when the predicted service life is surpassed, GWP impacts on additional life cycles are nullified. The calculations within this paper show that with the chosen allocation method, the reuse of the Café Horta structural elements contributed no additional environmental impact, thus incentivizing its reuse and preserving cultural heritage. In contrast, the beams in K118 were only in use for about 15 years, thus allocating more GWP to its recent life cycle. Lastly, although the chosen structures for this work are both exposed metal frames, **a 1-to-1 comparison of GWP between the buildings is not reasonable** because material choice affects the ECC, the intended structural use case and optimization are different.

5.1 *Limitations of the approach*

Although the findings of the proposed approach are promising, there are some limitations in the method. Laser scanning requires the structural components to be visible, but the elements are encased in many structural systems, thus preventing this approach. In addition, the developed technique for volumetric analysis contains opportunities for human error during the scanning, spot checks, and manual segmentation. Lastly, our approach was only used for homogenous materials; calculating GWP for hybrid structural systems would be more complex.

6 CONCLUSION

This paper demonstrated how to calculate the environmental savings from reused structural metal without prior documentation on the components. Lidar scanning helped capture the point cloud of exposed structural elements and develop a method to extract the component volume. (Previous literature focused on using Lidar as a method for tracking more raw material volumes, but Lidar had not been used for component volume extraction.) The second part of this paper conducted a GWP analysis of the scanned components and compared the savings of carbon dioxide equivalent emissions from reusing the components relative to using new components of the same volume. The latter work supplements existing literature by providing case-study applications and demonstrates the impacts of reusing structural components.

The calculation of material volume partially informs post hoc embodied carbon analyses of structures with lost or no prior documentation. This work aims to inspire future work on models based on artificial intelligence (AI) for structural point cloud segmentation and volume estimation for a more rapid analysis of buildings. Future research will focus on the automation and error resistance of the process. Deep learning approaches, currently applied for various interior classes, can be evaluated for automatic classification and segmentation of structural elements in different contexts. Semantic analysis of the voxel grid may allow for automatic calculation of the ideal voxel size without manual spot checks, as well as the detection and mitigation of occlusion areas. This work successfully demonstrates a reality capture workflow to estimate in-situ building component volumes in order to calculate GWP savings from reusing components.

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