

Designing with Reclaimed Steel: An Integrated Assessment Framework for High-Quality Structural Reuse

David GALLEGO*, Jonas M. THORN*, Stefan LANG*, Katja RINDERSPACHER^a, Diellza ELSHANI^b, Thomas WORTMANN^b, Achim MENGES^a

*Integrative Technologies and Architectural Design Research (ITECH), University of Stuttgart
Keplerstrasse 11, 70174 Stuttgart, Germany
davidg2999@gmail.com

^a Institute for Computational Design and Construction (ICD), University of Stuttgart

^b Institute for Computational Design and Construction/Computing in Architecture (ICD/CA), University of Stuttgart

Abstract

Direct reuse of structural steel can reduce embodied carbon by avoiding scrap remelting and primary production, yet its adoption remains limited because reclaimed members enter design with fixed dimensions, uncertain material properties, previous connections, damage, and project specific logistics. This paper presents a computational workflow for the high quality reuse of reclaimed linear steel components. The framework links pre demolition audit records, marketplace inventories, material testing, transport assumptions, and life cycle assessment data within an ontology based knowledge graph. Reasoning rules and queries infer profile matches, testing requirements, geometric and structural compatibility, and global warming potential, while a Rhino Grasshopper prototype enables designers to retrieve and compare reuse suggestions against virgin alternatives. The framework was evaluated using 857 reclaimed steel components from four urban mines. Under the applied LCA assumptions and system boundaries, the final demonstrator achieved approximately 44% lower global warming potential than a virgin material baseline. The results show that linked data can transform reclaimed steel inventories into computable structural design resources while exposing remaining challenges related to material uncertainty, connection detailing, reprocessing, and incomplete component documentation.

Keywords: structural reuse, design of spatial steel structures, computational design, life-cycle assessment, linked data

1. Introduction

The construction sector is a major source of raw material consumption [1], waste generation [2], and CO₂ emissions [3]. Reusing structural steel can reduce these impacts by avoiding energy intensive remelting and primary production [4], yet high quality reuse remains uncommon. In this paper, high quality reuse refers to the reuse of a component in its original or an equivalent function without significant loss of quality. A major barrier is that reuse reverses conventional structural design logic. Instead of selecting new members according to design intent and catalog availability, designers must work with existing stock characterized by fixed dimensions, uncertain material properties, previous connections, possible damage, and limited availability. Reclaimed components therefore need to be treated not only as physical elements, but also as data objects whose geometry, provenance, structural capacity, testing requirements, transport distance, and environmental impact must be matched to new design demands. Recent circular economy policies, Digital Product Passports, pre demolition audits,

and steel re-grading procedures are beginning to formalize component documentation and reassessment. DIN SPEC 91484 provides a basis for recording component information before deconstruction [5], while recent procedures define how reclaimed structural steel can be verified through testing and classification [6]. However, reuse relevant information remains fragmented across audits, material tests, marketplaces, technical standards, life cycle databases, and CAD/BIM models, making integration into early design decisions difficult.

This paper investigates whether reclaimed structural steel inventories can be operationalized as computable design resources during early stage structural design. To address this problem, the paper presents a computational workflow integrating reclaimed component inventories, structural requirements, material verification procedures, transport assumptions, and life cycle assessment data within a unified queryable workflow. Compatibility checks, reasoning rules, and assignment logic identify structurally feasible reuse candidates and evaluate their environmental and logistical implications against virgin alternatives. A Rhino Grasshopper prototype enables designers to retrieve and compare reuse suggestions during design development. The framework was evaluated using 857 reclaimed steel components from four urban mines and validated through iterative design development, structural verification, and partial full scale fabrication.

2. Literature Review

Existing research and practice address structural reuse through four complementary but weakly connected approaches: built precedents, computational design workflows, semantic data models, and environmental assessment tools. Kopfbau K.118 in Winterthur is a key precedent because it shows that reclaimed components can be implemented in a contemporary building while substantially reducing embodied carbon [7]. Its use of reclaimed steel beams, windows, and corrugated metal demonstrates that reuse can support architectural ambition rather than merely substitute conventional materials. The project demonstrates how reuse-oriented construction depends on component availability, geometry, and structural capacity.

Computational design workflows have begun treating material availability as an early-stage design parameter. Circular timber workflows, for example, generate structurally feasible configurations from reclaimed elements [8]. However, these approaches remain limited in workflows requiring evaluation of heterogeneous reclaimed stock against structural and environmental criteria.

Semantic approaches address the fragmentation of reuse data. The Steel Element Reuse Ontology (SERO) formalizes information on steel component condition, documentation, availability, and dismantling, supporting digital audits and semi-automated reasoning [9]. Yet it is primarily positioned on the audit side, while design teams require mechanisms that connect reclaimed components to specific design requirements, structural demands, and environmental comparisons.

Environmental assessment tools such as CAALA support life-cycle-based evaluation during planning, but generally operate around conventional materials and assemblies [10]. They do not automatically link reclaimed inventories with structural compatibility, testing requirements, or component-level assignment. The gap, therefore, is an integrated workflow that links reclaimed component data, structural compatibility, semantic reasoning, and embodied-carbon evaluation.

Existing approaches typically address these aspects independently: audit systems document reclaimed stock, computational workflows generate reuse-aware geometries, and LCA tools evaluate environmental impacts after design decisions are made. What remains insufficiently addressed is a workflow that supports iterative structural decision-making directly against available reclaimed inventories while incorporating material uncertainty, assignment logic, and fabrication constraints. The

proposed framework addresses this gap by transforming reclaimed linear steel components into computable design resources that can be queried, assessed, and assigned during structural design.

3. Methods

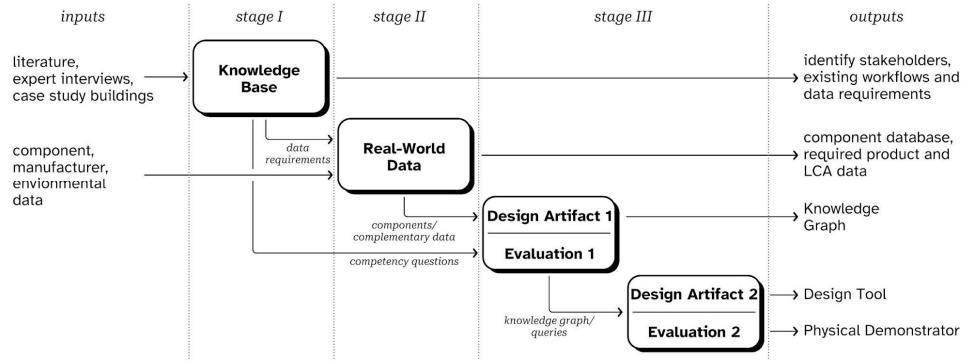


Figure 1: Overview of the conducted research from identifying expert knowledge on reuse of structural building components, over collection of real world data, to the design of two artifacts for evaluation, a knowledge graph integrating collected real-world data and expert knowledge, and a design tool prototype used to design a physical demonstrator.

3.1. Structural reuse workflow

The framework was developed to address a structural design problem: how to convert reclaimed steel components with fixed dimensions, uncertain material grades, and unknown histories into verified structural options that can be evaluated and assigned within a digital design environment. The workflow proceeds through five linked stages: pre-demolition data collection and material characterization; structural component representation and data integration; feasibility filtering and reuse-suggestion generation; life-cycle assessment and assignment optimization; and design-tool interaction with demonstrator validation. The knowledge graph serves as interoperability infrastructure linking structural assessment, environmental evaluation, assignment logic, and reclaimed component data within a unified reuse-oriented design workflow. The primary contribution is the integration of structural assessment, assignment optimization, environmental evaluation, and fabrication-informed validation within a reuse-oriented design workflow.

3.2. Reclaimed steel datasets and material characterization

Reclaimed component data were obtained from two sources: a pre-demolition audit of the ITECH Research Pavilion 2024 and an online catalog operated by Immobilien Basel-Stadt (IBS), yielding 12 and approximately 845 structural steel components respectively. These datasets were complemented with standard steel-profile specifications, material re-grading procedures, transport assumptions, and life-cycle assessment data from environmental product declarations. A targeted material testing campaign was conducted on representative profiles from the ITECH Pavilion stock, including chemical composition analysis, Brinell hardness measurement, Charpy impact toughness testing, and tensile testing. The initial conservative assumption classified all reclaimed profiles as S235; laboratory results revised this classification toward S275, reducing uncertainty in structural capacity evaluation and enabling more reliable assignment to load-bearing roles. To support interoperability between reclaimed inventories, structural requirements, and environmental evaluation, the workflow organizes project information into four operational entity categories. The workflow organizes information into four entities: reclaimed components, design components, standard components, and reuse suggestions.

Together, these connect available reclaimed members with structural demands, profile specifications, transport data, testing requirements, and environmental indicators.

3.3. Structural compatibility assessment

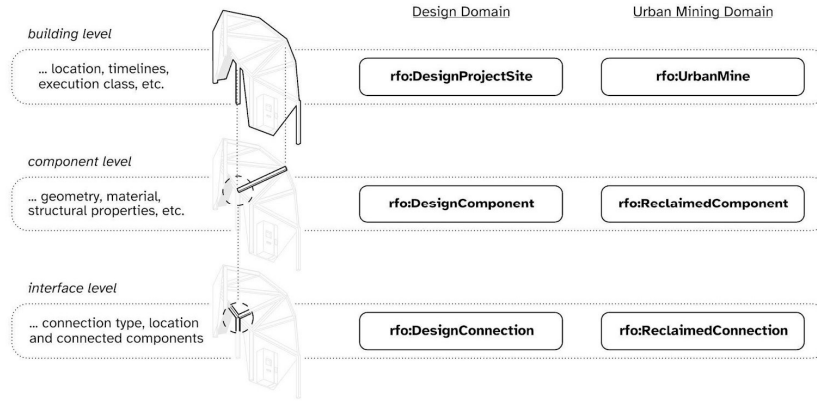


Figure 2: Information on building components is organized into two domains: the Design Domain addressing design requirements of the new project and the Urban Mining Domain addressing information about reclaimed building components. Additionally, information is spread hierarchically from building level, over component, to interface level.

Structural compatibility assessment relies on a unified data structure linking reclaimed inventories, design requirements, material verification data, and environmental indicators. Four entity types organize the workflow: reclaimed components, design components, standard components, and reuse suggestions. Reclaimed components store geometry, provenance, availability, condition, and material data including testing outcomes, while design components represent the structural demands and geometric constraints of the new structure. Standard components provide profile specifications for inferring missing information and defining virgin baselines. Reuse suggestions link reclaimed and design components, storing compatibility, testing requirements, transport distance, dimensional fit, and global warming potential. Static profile and environmental data are linked with project specific component and design data within one queryable workflow. Reasoning rules infer derived information from incomplete records. For example, incomplete reclaimed-component records can be linked to standard profile specifications through inferred cross-sectional matches, while construction year and documentation level trigger corresponding material verification requirements.

3.4. Matching, assignment, and structural verification

A reclaimed component is considered structurally feasible for a given design component when three conditions are simultaneously satisfied: its cross-sectional dimensions fall within the geometric constraints of the design member, its available length exceeds the required member length, and its inferred or tested structural properties meet the assigned design demands. The re-grading logic maps documentation level, construction year, and execution class to testing requirements, ensuring that the framework identifies not only whether a component is compatible, but also what verification steps are needed before structural assignment can be confirmed. Structural reuse introduces competing objectives that cannot be resolved through compatibility checks alone. Multiple reclaimed members may satisfy the same structural requirement while differing substantially in transport distance, cut-off waste, fabrication implications, and embodied carbon. The assignment problem is formulated as a constrained combinatorial matching problem in which feasible reclaimed-to-design component pairings are evaluated through a weighted cost function. The optimization was implemented through a constrained

weighted combinatorial assignment procedure, selecting assignments that minimize environmental and geometric penalties while satisfying structural and stock-availability constraints.

Because one reclaimed component can potentially satisfy several design members, and one design member may have multiple feasible candidates, the resulting set of reuse suggestions is filtered through a weighted assignment procedure. The assignment balances structural feasibility with environmental and logistical performance: embodied carbon, length fit, and transport distance are combined into a component-level cost function, and the optimization selects compatible pairings that minimize this cost while ensuring each design component receives at most one reclaimed member and the assigned length does not exceed the available stock. Assignment weights are user-defined and can be adjusted to prioritize local sourcing, carbon reduction, or geometric efficiency.

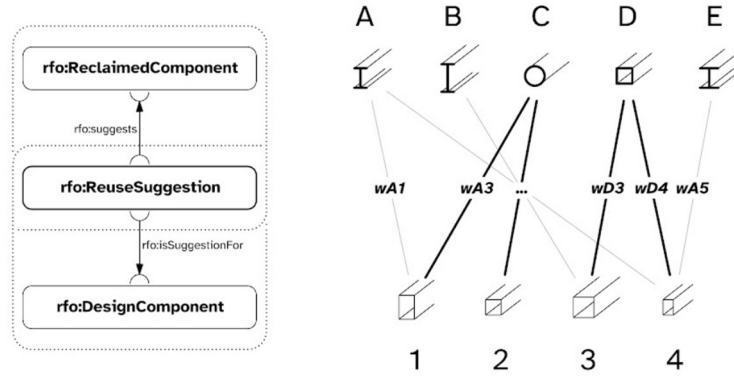


Figure 3: To solve the constrained combinatorial matching problem, weights w_{IJ} for individual assignments between a Design Component and a Reclaimed Component are calculated based on the information accessible through the respective Reuse Suggestion linking a Reclaimed and a Design Component.

3.5. Environmental assessment

Global warming potential (GWP) in kgCO_2eq is used as the sole environmental indicator. The assessment covers product-stage impacts for both reclaimed and virgin components, transport impacts where origin and destination are known or assumed, and avoided production burdens for reused members. Use-phase impacts are excluded. GWP values are drawn from environmental product declarations for standard steel sections and applied proportionally to component mass [11]. Results are aggregated at component and project level to report total embodied carbon, reuse share by weight, and carbon savings relative to a fully virgin baseline.

All reported reductions should be interpreted under the applied LCA assumptions and system boundaries. The assignment cost for each candidate pairing, as in (1), combines these environmental and geometric criteria. Each possible match between a design component and a reclaimed component is evaluated according to global warming potential, length difference, and transport distance:

$$\mathbf{w}_{ij} = \mathbf{w}_G \cdot \text{GWP}_{ij} + \mathbf{w}_D \cdot |L_j - L_i| + \mathbf{w}_T \cdot D_{ij} \quad (1)$$

where $\mathbf{w}_{ij}$ is the assignment cost for matching design component i with reclaimed component j , GWP_{ij} is the associated global warming potential, L_i and L_j are the required and available member lengths, D_{ij} is the transport distance, and $\mathbf{w}_G$, $\mathbf{w}_D$, and $\mathbf{w}_T$ are user-defined weighting factors.

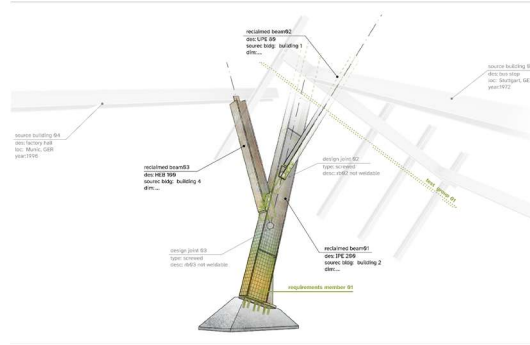


Figure 4: Visualization of the assignment and the information it is based on, across the interface, component and building level.

The optimization selects a subset of feasible reuse suggestions while ensuring that each design component receives at most one reclaimed component and that the assigned length does not exceed the available reclaimed stock length:

$$\min \sum_{ij} w_{ij} x_{ij} - P \sum_{ij} x_{ij} \quad (2)$$

$$\sum_j x_{ij} \leq 1 \quad \forall i, \quad \sum_i L_i x_{ij} \leq L_j \quad \forall j, \quad (3)$$

Here, x_{ij} is a binary decision variable indicating whether a reuse suggestion is selected, and P is a reward term that encourages assignment where feasible. The constraint equations ensure structural and logistical integrity: each design component receives at most one reclaimed member, and the assigned reclaimed length may not exceed the available stock length. A reward term further encourages assignment where feasible, preventing the optimizer from defaulting entirely to virgin components.

4. Results and Discussion

4.1 Results



Figure 5: Rendering of the design developed based on the proposed workflow (left) and the portion of the design realized from reclaimed steel beams as a full-scale demonstrator. (right)

The framework was evaluated through a demonstrator bus stop structure (approximately 12.0 m × 3.0 m × 4.0 m) using 857 reclaimed structural steel components from four urban mines, including 12 members documented through a pre demolition audit of the ITECH Research Pavilion 2024 and approximately 845 from the Immobilien Basel Stadt online catalog. The demonstrator typology was

selected because it combines moderate structural complexity, repeated linear members, exposed connection conditions, and realistic fabrication constraints within a manageable experimental scale. The knowledge graph integrated component geometry, provenance, material data, and environmental indicators within a single queryable structure. Geometric and structural compatibility queries were fully answerable, while economic and detailed condition data remained incomplete due to gaps in the source datasets.

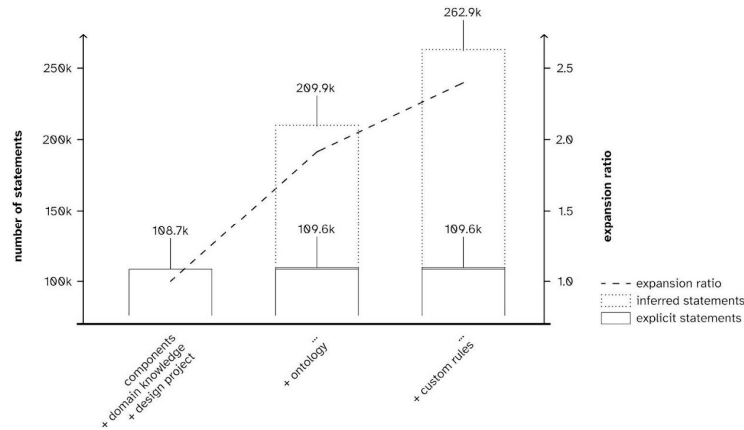


Figure 6: Expansion ratio and number of statements in the developed knowledge graph.

In the first design iteration, 13 structural members were assigned to 10 reclaimed components, achieving approximately 95% reclaimed steel by weight. Embodied carbon was reduced from 326 kgCO₂eq for a fully virgin baseline to approximately 159 kgCO₂eq, a 51% reduction. However, this configuration relied on components sourced from Basel with more than 3 m of residual cut off length, exposing logistical and fabrication inefficiencies. This demonstrated that maximizing reclaimed mass alone does not necessarily produce practically or environmentally robust reuse outcomes once fabrication and sourcing constraints are considered.

The second iteration introduced verified material data through tensile, chemical composition, Brinell hardness, and Charpy impact testing, revising the initial conservative S235 classification toward S275 for the ITECH Pavilion profiles. Assignment weights were adjusted to prioritise local sourcing, while the geometry was refined to reduce cantilever spans and cut off waste. This configuration used 8 reclaimed and 10 virgin components, achieving 71.2% reclaimed steel by weight at 214 kgCO₂eq.

Final iterations addressed constructability constraints including node congestion, acute member intersections, limited weld access, and profile inconsistencies. Member orientations were adjusted, sections consolidated into IPE 80 and IPE 120 profiles, and column assignments pinned to specific reclaimed members. The final demonstrator comprised 18 structural elements, including 8 reclaimed and 10 virgin components, achieving approximately 75% reclaimed steel by weight and 198 kgCO₂eq against a virgin baseline of 355 kgCO₂eq, corresponding to approximately 44% lower embodied carbon under the applied LCA assumptions and system boundaries.

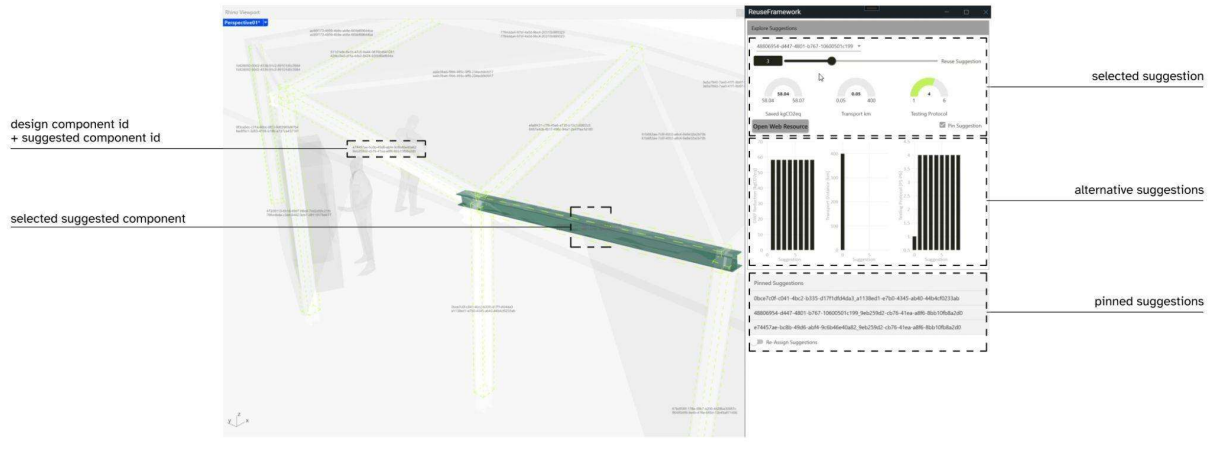


Figure 7: Annotated screenshot of the design tool's interface for exploring Reuse Suggestions for a user-selected Design Component.

Structural verification confirmed Eurocode compliance [12], with utilization ratios between 0.19 and 0.75 and deflections within serviceability limits. A partial full scale node was fabricated to validate geometric accuracy, member traceability, and constructability at connection level, demonstrating that the workflow supports precise and structurally verified reuse outcomes.

4.2 Findings

The most significant fabrication finding is that structural and geometric compatibility are necessary but insufficient conditions for buildable reuse. Components can satisfy cross section, length, and load capacity requirements while remaining problematic at the connection level due to weld access limitations, node congestion, acute intersection angles, and reprocessing requirements from prior modifications. These issues are not captured by current matching logic and indicate the need for connection aware reuse assessment that explicitly represents connection history, damage zones, existing plates and holes, and required reprocessing. Fabrication feedback therefore becomes a necessary input to reuse oriented structural decision making rather than a downstream validation step.

A second finding concerns the division of roles between the computational framework and the design team. The tool generated and ranked feasible reuse suggestions, while engineers and designers resolved conflicts related to assembly sequencing, node geometry, and structural coherence. The framework structures uncertainty and exposes trade-offs between structural feasibility, environmental performance, and constructability, but it does not replace engineering judgment during early stage structural design.

4.3 Discussion

The knowledge graph functions as integration infrastructure rather than an end in itself. It connects audit records, material testing outcomes, standard-profile data, structural demands, transport information, and LCA values in a single queryable structure, making the five workflow stages interoperable without manually coordinated data handling. The contribution is the integrated workflow this enables: a structural designer can query feasible reclaimed members, inspect environmental trade-offs, and compare assignments within one environment. This positions the framework at the precise point where current practice breaks down, which is between audit-stage component documentation and design-stage structural decision-making.

The reported carbon reductions must be read under the applied LCA assumptions and system boundaries. The final 44% reduction is more credible than Iteration 01's 51% figure because later iterations incorporated local sourcing constraints, verified material data, and realistic fabrication conditions. Reported reuse percentages and carbon savings are sensitive to system-boundary decisions, particularly the treatment of transport, cut-off waste, and reprocessing energy, making consistent LCA boundaries essential for meaningful comparison across reuse projects.

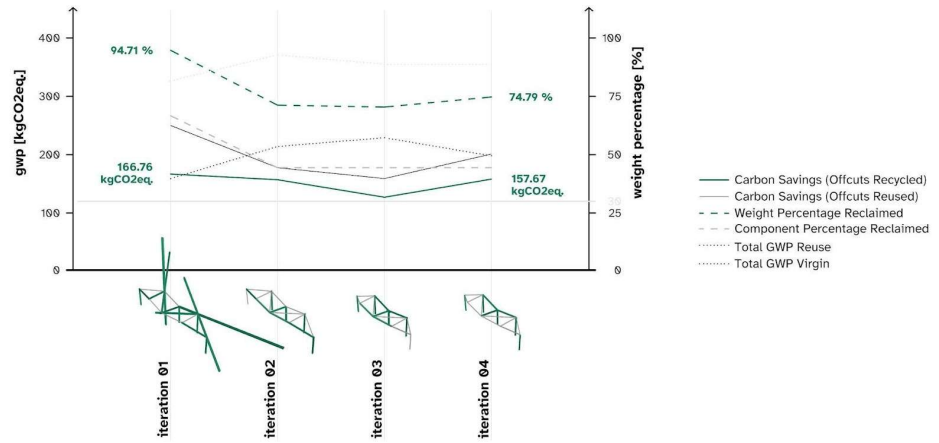


Figure 8: Development of global warming potential (kgCO₂eq.) of the structure and weight percentage of reclaimed components for the 4 design iterations made before arriving at the final design for the bus stop.

The iterative evolution of the demonstrator illustrates that reuse-oriented structural design is not a linear process of assigning reclaimed members to predefined geometry, but a reciprocal negotiation between available stock, structural performance, fabrication constraints, and environmental objectives.

Several limitations of the current framework are themselves research findings. The workflow addresses standardised linear steel components only; connection histories, detailed damage descriptions, and reprocessing costs were only partially available in the source datasets. The design tool supports selection and evaluation but does not generate alternative geometries in response to available stock. Matching logic is deterministic, whereas probabilistic approaches would better reflect the uncertainty inherent in reclaimed material properties. The demonstrator scale also limits conclusions regarding larger structural systems where transport logistics, inventory management, and connection standardization may become substantially more complex.

These gaps identify what still blocks scalable structural reuse: not the absence of computational tools, but the absence of consistent, interoperable component data across the supply chain. Standardised pre-demolition audit formats, Digital Product Passports, and component-level material records that persist through the demolition-to-reuse cycle are prerequisites for broader adoption.

5. Conclusion

This paper presents an integrated workflow for the high quality reuse of reclaimed linear structural steel components. By linking pre demolition audit data, material testing results, structural assessment, and environmental evaluation within a unified data structure, the framework transforms reclaimed steel inventories into computable structural design resources. Applied to 857 reclaimed steel components and validated through iterative design development and partial fabrication, the workflow produced a

structurally verified demonstrator with approximately 44% lower embodied carbon than a virgin material baseline under the applied LCA assumptions and system boundaries.

The study demonstrates that reuse oriented structural design depends not only on geometric and structural compatibility, but also on fabrication constraints, connection conditions, and material verification. Extending the framework toward connection aware reuse assessment therefore represents an important next step. More broadly, the results show that structural reuse becomes viable at design scale when reclaimed inventories participate directly in structural decision making rather than being treated as secondary procurement constraints after design completion.

6. Acknowledgements

This research project was realized as a Master's thesis in the Integrative Technologies and Architectural Design Research M.Sc. Program (ITECH) at the University of Stuttgart, Germany, led the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (itke). The research is partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/2 – 390831618.

References

- [1] B. C. Guerra and F. Leite, “Circular economy in the construction industry: An overview of United States stakeholders’ awareness, major challenges, and enablers,” *Resources, Conservation and Recycling*, vol. 170, p. 105617, 2021.
- [2] N. Islam et al., “Review on sustainable construction and demolition waste management - Challenges and research prospects,” *Sustainability*, vol. 16, no. 8, 2024.
- [3] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang, “Carbon emission of global construction sector,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1906–1916, 2017.
- [4] P. Riegler-Floors and A. Hillebrandt, “Cost comparisons of conventional and urban mining design constructions,” in *Manual of Recycling*, A. Hillebrandt et al., Eds. Munich: Detail Business Information GmbH, 2019, pp. 120–133.
- [5] DIN SPEC 91484:2023-09, *Verfahren zur Erfassung von Bauprodukten als Grundlage für Bewertungen des Anschlussnutzungspotentials vor Abbruch- und Renovierungsarbeiten (Pre-Demolition-Audit)*. Berlin, Germany: DIN Media GmbH, 2023.
- [6] P. Dietsch et al., *Vorbereitung der Wiederverwendung von bestimmten Bauprodukten des Holz- und Stahlbaus: Schlussbericht*. Karlsruhe, Germany, 2025.
- [7] “K118 Kopfbau Halle 118 / baubüro in situ,” *ArchDaily*, 2021. [Online]. Available: <https://www.archdaily.com/968958/k118-kopfbau-halle-118-hauburo-in-situ>. [Accessed: Mar. 24, 2025].
- [8] M. Luczkowski et al., “Proposal of interactive workflow for circular timber structure design,” in *Proceedings of the World Conference on Timber Engineering*, Oslo, Norway, 2023, pp. 19–22.
- [9] L. Schönfelder et al., “A steel element reuse ontology for building audits in circular construction,” *Developments in the Built Environment*, vol. 21, p. 100638, 2025.
- [10] “CAALA,” CAALA GmbH. [Online]. Available: <https://www.caala.de/use-cases/caalamachbarkeitsstudien>. [Accessed: Oct. 8, 2025].
- [11] Sphera Solutions GmbH, “Baustahl: Profile und Stabstahl (de),” *ÖKOBAUDAT*, 2023. [Online]. Available: <https://oekobaudat.de>. [Accessed: Sep. 30, 2025].
- [12] DIN EN 1993-1-1:2025-04, *Eurocode 3 – Design of steel structures – Part 1-1: General rules and rules for buildings*. Berlin, Germany: DIN Media GmbH, 2025.