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SCAN2BEAMS: MOVING TOWARDS AUTOMATED MODELLING AND ANALYSIS OF STRUCTURAL INDUSTRIAL BUILDING STOCK

Julia Reisinger[1], Diana Marin[2], Philipp Rufinatscha[1], and Peter Kán[2]
[1] TU Wien Institute of Building and Industrial Construction, Vienna
[2] TU Wien Institute of Visual Computing and Human-Centered Technology, Vienna

Abstract

Manual creation of as-built models for Finite Element Method (FEM) analysis is labour-intensive and error-prone, hindering effective reuse of building structures. SCAN-to-FEM technology automates the capture and analysis of building stock, lacking efficient methods for converting point cloud or photogrammetry data into analytical FEM models of skeleton structures. This paper introduces Scan2Beams, a framework for transforming 3D photogrammetry data of industrial buildings into parametric structural meshes of the load-bearing structure. Validated through a use case, Scan2Beams enables integration of point cloud data into structural analysis workflows and eliminates manual modelling. Future research includes automated joint behavior recognition and retrofitting suggestions.

Introduction

Sustainable development in the built environment has accelerated significantly in recent decades, marked by a shift toward reusing and adapting existing infrastructures (Mercader-Moyano and Esquivias, 2020, Owojori et al., 2021). Retrofitting buildings has proven to be environmentally sound and optimizes energy and resource performance (Shaikh et al., 2017), while adaptive reuse can reduce major environmental impacts by 53-75% (Hasik et al., 2019). The regeneration and utilization of old industrial buildings in and around cities has become a focus of urban development, driven by urban renewal and industrial structural adjustment (Jia et al., 2023). Reusing industrial buildings requires design solutions that accommodate new user demands to ensure long-term value and sustainability (Zheng et al., 2022), and adaptive reuse of industrial heritage has also been shown to be economically viable (Dell'Anna, 2022).

However, the reuse of industrial buildings presents specific challenges that differ from those encountered in residential or historical structures. Industrial buildings are often large-scale, cluttered environments that include not only load-bearing elements but also an abundance of non-structural components such as machines, pipes, façades, and technical installations. This high level of geometric and functional complexity complicates structural assessment and model generation. Moreover, the actual load-bearing capacity and suitability of these structures for adaptation, especially for vertical expansion and upgrading to minimize land sealing—are typically unknown. In current planning and analysis processes this necessitates comprehensive plan reviews, time-consuming on-site inspections, and the manual development of structural analysis models.

While much of the current research on digital modeling of existing buildings continues centers on Scan-to-Building Information Modeling (Scan-to-BIM) techniques (Rashdi et al., 2022, Valero et al., 2021, Zhao et al., 2021) or focuses on cataloging materials for deconstruction (Heisel et al., 2022), Scan-to-Finite Element Methods (SCAN-to-FEM) are gaining attention for their potential to directly support structural analysis and retrofitting. These methods enable the reconstruction of 3D building models for material quality analysis (Paral et al., 2021), structural assessment of historical buildings (Alfio et al., 2022; D'Altri et al., 2023) and automated point cloud-to-geometry conversion for FE analysis (Selman et al., 2022).

However, existing SCAN-to-FEM workflows have been developed primarily for heritage buildings or tunnel structures with relatively clean geometric structures and well-defined masonry components. These methods often aim to model the entire environment, generating finite elements for all elements visible in the point cloud. Such an approach is not suitable for industrial contexts, where only the structural skeleton is relevant, and the surrounding complexity may obscure the load-bearing system. This highlights the need for a more targeted, selective method tailored to industrial building stock.

This paper introduces Scan2Beams, for the automated generation of structural geometry meshes from point cloud and image data, specifically designed to extract and model load-bearing skeleton systems within industrial buildings. The method involves preprocessing large-scale point clouds, projecting and segmenting the data to identify axis-aligned three-dimensional line structures indicative of load-bearing elements. These are then converted into a parametric representation suitable for Finite Element Analysis (FEA). Unlike conventional approaches, our pipeline focuses solely on structural elements and omits non-structural features, enabling the direct creation of simulation-ready FEM models without manual cleanup or meshing steps.

The research is part of the RE:STOCK INDUSTRY project, funded by the Austrian Research Promotion Agency, which aims to develop an automated, life-cycle-oriented methodology for capturing, analyzing, and documenting the structural characteristics of industrial building stock. The overarching goal is to support comprehensive assessments for reuse, modernization, and vertical extension of these structures.

The paper begins with a literature review, followed by a detailed presentation of the research methodology. The core section introduces the developed Scan2Beams framework, which is validated through a proof-of-concept application on a real reinforced concrete building structure. The paper concludes with a discussion of the method's implications and outlines directions for future research.

Literature Research

The review examines current research on Scan-to-FEM methods for retrofitting of existing buildings, with a focus on how point cloud data is processed and translated into finite element (FE) models. Studies were identified through SCOPUS and Web of Science using targeted keywords such as “Scan to FEM,” “TLS to FEM,” “Cloud2FEM,” “Point Cloud,” “LIDAR Scan,” “Finite Element Modelling,” and related structural terms like “node,” “skeleton lines,” and “support.” Inclusion was limited to peer-reviewed, English-language publications up to March 2024.

Dominant Approaches and Key Contributions

A significant proportion of the reviewed studies — eight in total — build on the foundational work of Castellazzi et al. (2015). Their semi-automated Cloud2FEM approach transforms laser-scanned point clouds into FE models by decomposing complex structures into 2D slices, voxelizing them into 3D matrices for efficient modeling. This method was further developed into open-source software Castellazzi et al. (2022), enabling the automated generation of hexahedral FE meshes, particularly suited for heritage buildings.

Bitelli et al. (2018) validated this method on the San Felice sul Panaro fortress, demonstrating its effectiveness for historical preservation through high-resolution TLS and photogrammetry. Likewise, Cui et al. (2023), advanced automation by introducing the Clock Simulation Extraction (CSE) algorithm to create FEMs of tunnel structures directly from point clouds, segmenting the tunnel into equidistant slices with assigned topological information.

Other notable advancements include D'Altri et al., 2023 , who combined slicing strategies with solid model generation for cultural buildings; Yang et al. (2024) who integrated terrestrial laser scanning (TLS) with FEM for tunnel deformation analysis; and Funari et al. (2021), who proposed a parametric SCAN-to-FEM pipeline using generative programming to support digital twin creation of masonry structures.

The field has also seen diversification with Wang et al. (2022) introducing *PIMesh*, an innovative method applied in surgical simulations, and Selman et al. (2022), automating the conversion of point clouds into structured 3D models using cuboid recognition for potential reconstruction of cultural heritage sites.

Research Gaps and Contribution of this Work

While the reviewed studies demonstrate substantial progress in automating point cloud to FEM conversion, most focus on cultural heritage or tunnel structures, where the entire scanned environment—including non-structural elements—is modeled. These approaches are not directly applicable to industrial buildings, where load-bearing structures are embedded within highly cluttered environments including machinery, pipes, façades and inner partition walls, and other architectural noise. Existing methods typically aim to model entire scenes, rather than discriminate between structural and non-structural components. This limitation poses a significant bottleneck in applying Scan-to-FEM approaches to large-scale, operational industrial buildings, where only the load-bearing skeleton is of interest for retrofitting or structural simulation.

This paper addresses the identified research gap by introducing a novel pipeline that automatically identifies and extracts only the load-bearing structure from dense point clouds of entire industrial buildings. In contrast to previous approaches that generate finite element models of all visible geometry—including non-structural elements such as pipes, machines, and façades—our method focuses exclusively on the structural skeleton. It isolates the relevant structural components, detects axis-aligned three-dimensional line segments indicative of load-bearing frameworks, and produces a clean, simulation-ready finite element geometry without the need for intermediate manual steps.

Research Methodology

Building on the findings of the literature review, this paper presents Scan2Beams, a geometry-based method for processing point cloud data from industrial buildings to identify and classify structural elements, isolate load-bearing components like columns and beams, assign dimensions, and organize the data for seamless export to FEM software for automated model generation. The algorithm was developed in Python and designed as a fully automated pipeline from input to FEM-ready output, with limited manual intervention for parameter adjustment.

In this research, the point cloud input data was reconstructed from images captured via photogrammetry.

Images were collected using a GoPro camera mounted on a drone, which navigated the interiors of seven typical industrial buildings in Austria under controlled conditions. Flight patterns and imaging strategies were optimized to ensure full spatial coverage and high-resolution detail suitable for photogrammetric reconstruction. The dataset comprises structures with reinforced concrete columns and beams, or hybrid steel frameworks.

To evaluate the effectiveness of Scan2Beams, the method was applied to a case study involving a representative industrial building constructed in 1980, characterized by a precast concrete skeleton. Performance was assessed through manual validation against architectural floor plans, focusing on geometric accuracy and the correct classification of structural elements. The structural analysis software Dlubal RFEM (Dlubal, 2021) was used to validate the practical usability of the exported geometry by successfully importing the output for finite element modeling and simulation. The remaining six buildings in the dataset will be analyzed in future work to assess generalizability across different structural layouts, geometries, materials and scanning conditions.

Scan2Beams Pipeline and Proof of Concept

The proposed workflow for generating FEM-compatible structural analysis models of industrial buildings from point clouds comprises three main stages, with the Scan2Beams framework implementing the first step - see Figure 1: (1) Data collection and preparation, involving the acquisition of point clouds, images, and plan documentation; (2) Data processing and feature extraction, where structural elements are recognized, classified (e.g., materials, joints, cross-sections), and enriched with plan-derived information; and (3) Algorithm development for FEM model generation, automating geometry creation, joint behavior modelling, and material property integration.

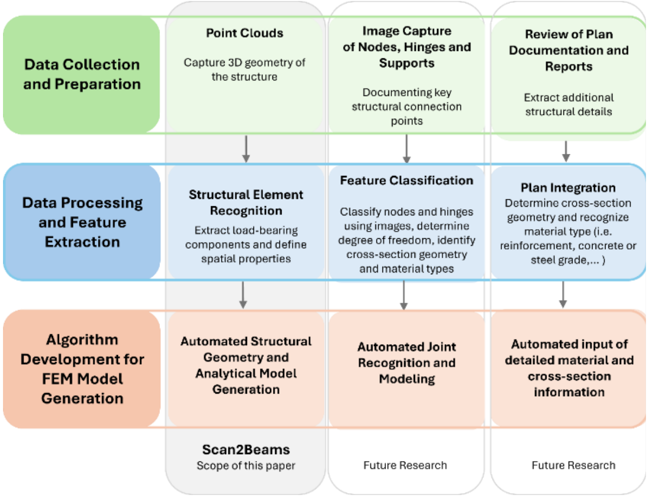

Figure 1: Proposed workflow for generating FEM-compatible structural analysis models of industrial buildings with a focus on the Scan2Beams framework as the initial step.

The received geometric analytical model obtained from Scan2Beams represents the first step toward a fully reconstructed FEM-compatible model that integrates geometry, materials, joint behavior, and structural condition—enabling the automated development of comprehensive FEM models from existing building data in future applications.

The Scan2Beams framework focuses on the automatic reconstruction of parametric models from point cloud data for analyzing existing structural frameworks. Geometry-based techniques are applied to identify and extract vertical and horizontal structural elements—such as beams and columns—along with their geometric properties, including dimensions and thicknesses. Importantly, the output of Scan2Beams includes only structural elements, while non-structural components such as machinery, installations, and interior furnishings are intentionally excluded. The process begins with a heuristic search for point carriers aligned vertically or horizontally in the point cloud, representing potential load-bearing components.

Point Cloud Processing and Grid Discretization: Given a 3D point cloud input, which is a collection of 3D coordinates representing the structure, the data is discretized into a structured grid with a user-defined resolution (referred to as *grid_resolution*). Within each grid cell, points are accumulated into cells, allowing the evaluation of point density, spatial distribution and structural relevance. This discretization provides an organized framework to track point memberships and structural relevance across the scan, forming the foundation for subsequent extraction steps.

Structural Element Extraction: Scan2Beams incorporates a structural element extraction process leveraging geometric information about the configuration of industrial skeleton structures from the point cloud data. By assuming that beams and columns are axis-aligned and typically span entire dimensions (e.g., columns extend continuously from the floor to the ceiling), the problem is simplified to axis-aligned line detection. The extracted lines represent the core geometry of the structural elements, which are further refined and post-processed to improve precision and reliability.

Hough Transform for Line Detection: To identify the linear geometry of structural beams and columns, a basic Hough transform is applied on each axis-aligned plane (i.e., on each of the xy, xz, and yz planes) to the discretized grid. This technique detects linear features within the dataset, which correspond to potential candidates for structural elements. These detected lines are then subjected to refinement processes, which involve filtering based on orientation, length, density and spatial arrangement – see Figure 2. This step ensures the accurate classification and reconstruction of columns and beams within the scanned environment.

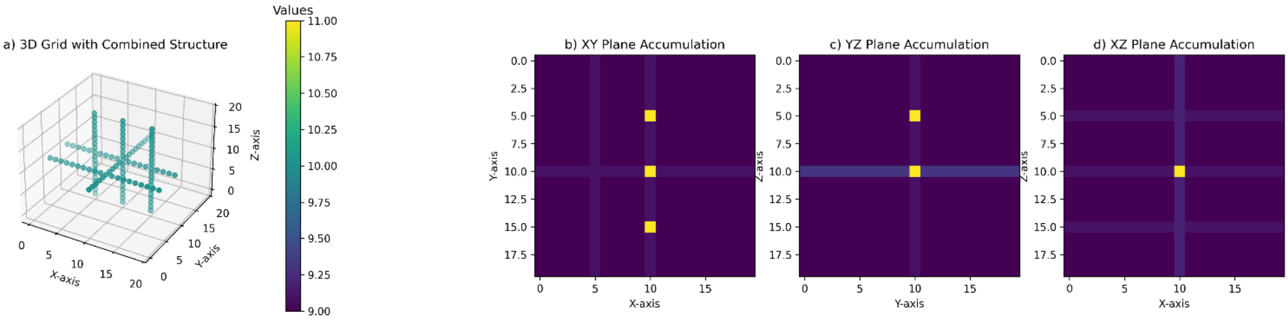

Figure 2: Hough accumulator on each plane of the 3D input. Points exist along 3D lines in a) and are accumulated into each axis-aligned plane in b), c) and d). We observe highlights where lines exist in the 3D domain of each projected plane.

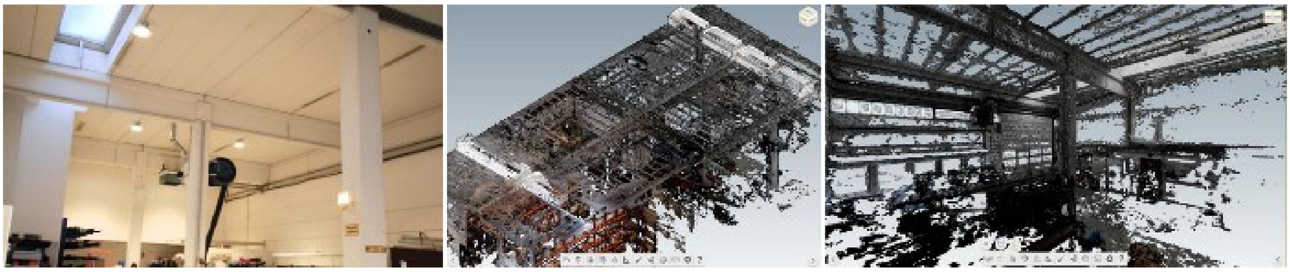

Figure 3: Captured Use-Case and Use-Case for Proof of Concept

Reconstruction of Structural System in a FEA program: The final output of the pipeline is a CSV file containing precise geometric and parametric data, such as dimensions, coordinates, and alignment of beams and columns. This file is specifically formatted for seamless integration into Dlubal RFEM, a widely used FEA software. The program interprets the CSV data to automatically generate nodes, line elements, and material properties corresponding to the reconstructed beams and columns.

Proof of Concept

The use case for the proof-of-concept represents a typical example of an industrial building structure, providing a practical foundation for testing the proposed Scan2Beams pipeline - see Figure 3. The building is located in the industrial center of Lower Austria. Constructed in 1980, the building has undergone multiple expansions and renovations in 1987, 1994, 2008, and 2021, reflecting its evolving functional and structural requirements. The building is a two-aisled hall with a prefabricated reinforced concrete skeleton construction, complemented by aerated concrete walls, a ventilated trapezoidal sheet metal facade, and a warm roof. The roof's load-bearing structure is composed of aerated concrete roof elements, designed to provide both structural stability and thermal efficiency.

The structural details are the following:

- Columns and Room Height: Precast concrete columns with forked supports, each having a cross-section of 40 × 40 cm. These are positioned in three rows with a 6-meter axis distance between them. The column height, thus room height is 6.10 meters.
- T-Beams: Two single-span precast concrete T-beams are supported on the forked columns, with each beam having a length of 6.00 meters and 0.80 meters in height.

Figure 4 presents the computational Scan2Beams pipeline applied to the use case. The pipeline comprises six main steps: 1. Point Cloud Input, 2. Detect Lines, 3. Strong Lines, 4. Extracted Structure, 5. Beams and Joints, 6. FEA program import. Figure 4 (1) shows the 3D scan of the industrial hall. For each plane, the algorithm projects all points on the plane, aggregating them into grid-size cells. A threshold, *per_axis_threshold*, is used on each axis to accommodate potential structural variations across the hall dimensions. Planar coordinates of columns containing more points than the given threshold are retained for further analysis, and they constitute the detected lines, see Figure 4 (2). These lines exist as normals to the aggregation planes in the full three-dimensional space.

Since some detected lines may also represent non-structural elements, such as walls, additional filtering is required. For each line, we impose a secondary threshold, *per_cell_threshold*, that specifies the minimum number of points required in a cell for it to be considered structurally relevant. This follows from the assumption that structural beams and columns are continuous in the scanned input. A *strength_percentage* criterion ensures that only lines with a sufficient percentage of filled cells are marked as strong, for further processing. For each such strong line, we record the first and last cells satisfying the threshold, defining the line's endpoints as seen in Figure 4 (3).

The filtered strong lines should represent part of candidate beams (usually in the form of edges). To extract the full beams as cuboidal structures, we cluster the existing lines using an epsilon parameter, *cluster_epsilon*. This parameter defines the neighborhood size required to group lines into a beam (i.e. if two lines are closer than epsilon, we connect the two lines). An epsilon-neighborhood graph is computed for each plane where line coordinates exist, and connected components are extracted. Each connected component represents a structural beam, defined by its center of mass (calculated as the mean of all lines within the cluster) and radius (the average distance from the center to each point). We further remove clusters that only contain one line, as structural elements are usually thick and would comprise multiple strong lines. This yields a set of cuboidal representations for each beam – Figure 4 (4).

To extract the joints that connect the existing beams, we examine all pairs of lines from different aggregation planes to identify geometric intersections, as lines in the same plane do not intersect. This is because, for each plane, its lines are defined as normals to the plane. We use approximate intersection (if the two lines are within *intersection_epsilon* distance, we consider them as intersecting). We use the same threshold to merge joints that are close together, as they should be modelled as a single joint. Each beam stores the joints that affect it. We further create a joint for the start and end of each beam, if there are no joints placed there already. To accurately model the beam network, beams are segmented based on joint connectivity. For each line, we order joints along its free axis, dividing them into segments between consecutive joints. The results are presented in Figure 4 (5).

The processed model is outputted in two CSV files: one detailing joints (nodes) with their positions, and another listing beams, where each segment is defined by its node identifiers. We import the data into the FEA program DlubalRFEM, using a customized script – Figure 4 (6).

Throughout the algorithm, various parameters are left to the user's choice such that the results match the expected structure of the scanned building. These parameters can be influenced by the quality of the scan, its density, and the sizes of various real-life structural elements.

The method currently facilitates the automated identification, extraction, and modeling of the structural systems in skeleton structures; however, its limitations include the manual post-processing requirements for load settings, joint behavior, and detailed material properties.

Discussion

While this paper does not yet include a quantitative evaluation due to the absence of ground truth beam data for the scanned use case, we manually validated the extracted structural geometry against the known layout of the building and confirmed alignment with observable structural elements such as columns and beams with the planning documents. The Scan2Beams pipeline successfully identified axis-aligned columns and beams that aligned well with the expected positions, dimensions, and overall skeleton layout of the structure. Since the point cloud is based on real-world measurements, it provides a reliable geometric basis for reconstruction.

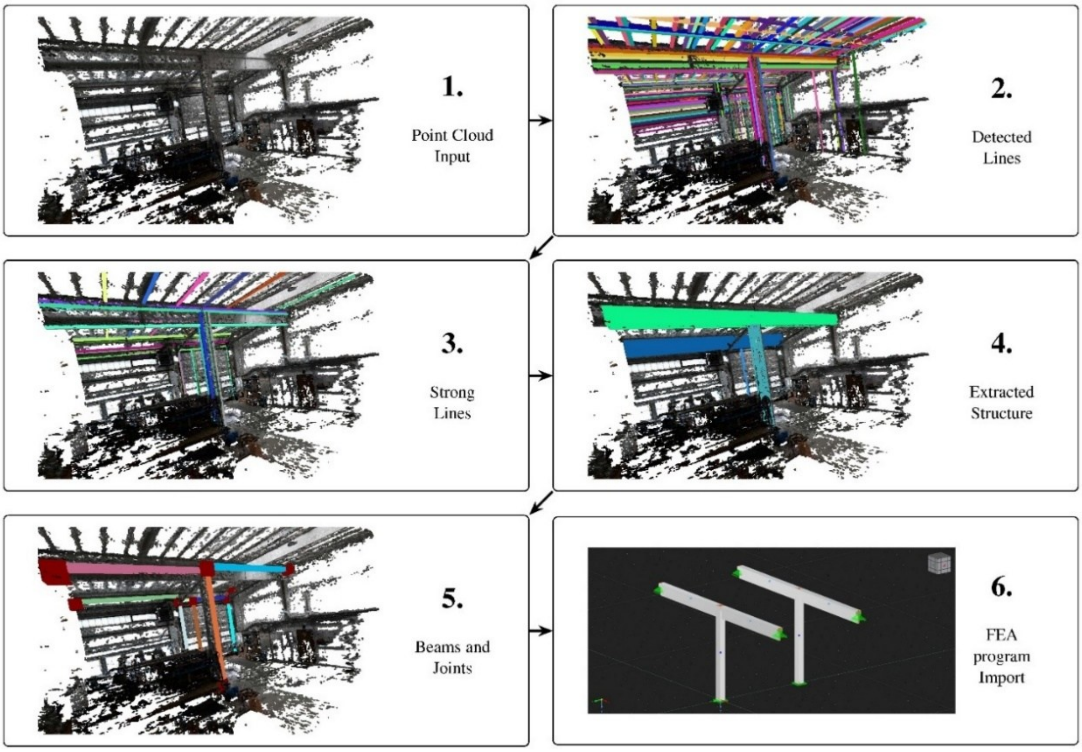

Figure 4: Scan2Beams computational pipeline applied to an industrial hall with a prefabricated reinforced concrete structure.

As part of our ongoing research, we plan to extract reference data from architectural floor plans and as-built documentation to perform a comprehensive quantitative evaluation using standard metrics such as accuracy, precision, recall, and geometric deviation in terms of positioning, dimensions, and connectivity, along with a wider set of use cases to validate the robustness and adaptability of the method across different building types and scanning conditions.

Conclusion and Future Outlook

In this paper, the Scan2Beams framework for automated structural geometry extraction from point clouds and FEM model preparation was presented. While significant advancements have been made in the Scan-to-FEM field, recent efforts have largely focused on traditional heritage buildings and tunnel structures. In contrast, research addressing the reuse of industrial structures remains limited.

This paper introduced and demonstrated the Scan2Beams method, which successfully identifies and classifies structural elements of a skeleton construction from point clouds of an industrial building. As part of this work, we implemented a proof-of-concept on a real use case capable of extracting lines and nodes corresponding to columns, beams, and their intersections. We differentiate our method from existing Scan-to-FEM approaches by extracting and reconstructing only the relevant structural elements in the scene – columns and beams. The initial results confirm the feasibility of applying Scan-to-FEM techniques to industrial buildings, offering a critical step toward integrating automated workflows into this underexplored domain.

By addressing the underexplored domain of industrial structure reuse, Scan2Beams contributes to sustainability goals by enabling the efficient and targeted repurposing of existing buildings. The method facilitates reuse by significantly reducing the need for manual modeling and structural assessment, providing engineers and planners with accurate, simulation-ready FEM models derived directly from scan data. This makes it easier to assess the structural viability of retrofitting, vertical extension, or function transformation early in the planning phase. As a result, Scan2Beams helps integrate digital workflows into the reuse process, ultimately lowering costs, saving time, and supporting more informed and sustainable design decisions.

Future research will focus on expanding the capabilities of Scan2Beams. We plan to automate the parameter choice in our algorithm, as some of the input characteristics can be inferred directly from the point cloud. At the same time, we aim to maintain user flexibility for adaptation to various project contexts. Next steps include extracting the basic type of connection at endpoints (e.g., fixed or flexible joints), integrating symmetry priors to improve detection accuracy, and identifying the cross-section shape and dimensions of structural elements. This will involve analyzing 2D slices along each beam and enriching geometric data with plan documentation and material catalogues. Additionally, we plan to use learning-based methods to classify joint types and degrees of freedom based on labeled image datasets.

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