ZeroWaste

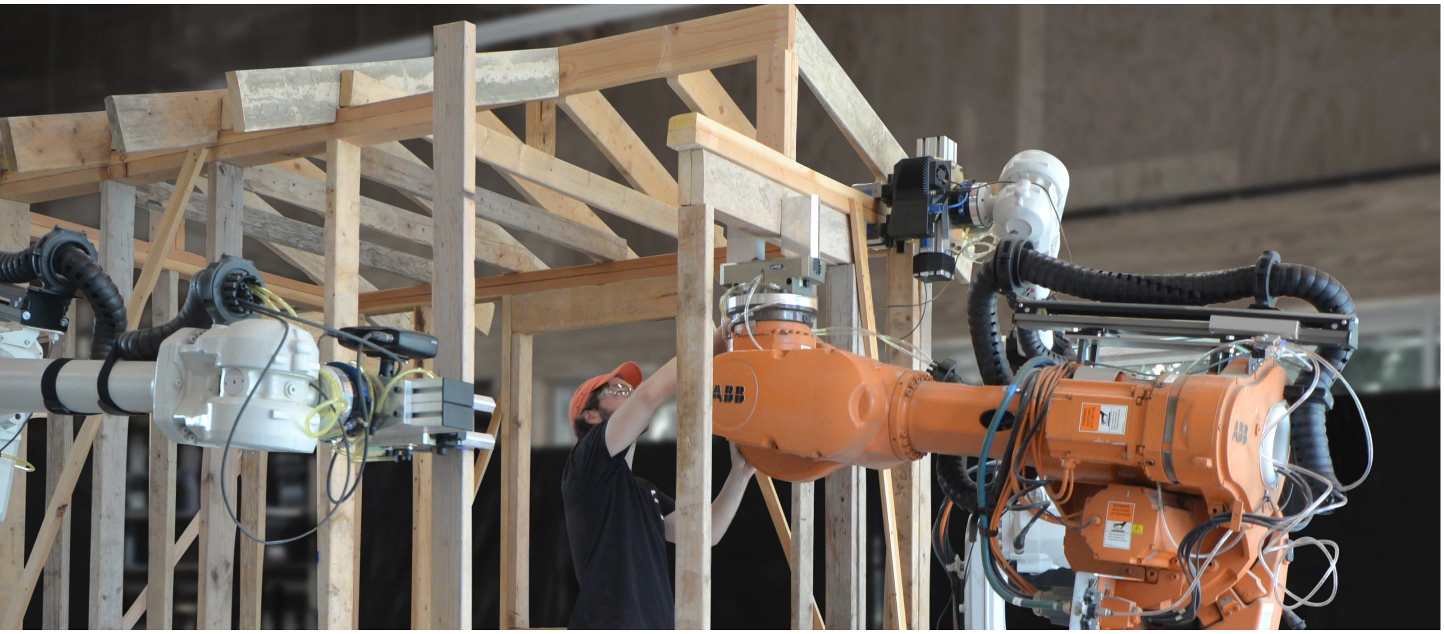
Edvard P. G. Bruun
Princeton University

Erin Besler
Princeton University

Sigrid Adriaenssens
Princeton University

Stefana Parascho
École Polytechnique Féderale
de Lausanne

Towards Computing Cooperative Robotic Sequences for the Disassembly and Reuse of Timber Frame Structures



1

1 Three industrial robotic arms (2xIRB4600 & 1xIRB7600) cooperatively sequenced to alternate in their function of supporting and removing elements during the scaffold-free disassembly of a conventional timber stick frame structure

ABSTRACT

ZeroWaste is a project about repositioning existing timber building stock within a circular economy framework. Rather than disposing of these buildings at the end of their life, the goal is to view them as stores of valuable resources that can be readily reused. By doing this, material life cycle becomes an integral design consideration alongside planning for the efficient disassembly and reuse of these structures. In this paper, the computational workflow is presented for the first phase of the project: planning a cooperative robotic disassembly sequence for the scaffold-free removal of members from existing timber structures. A pavilion-scale prototype is first constructed, in the Embodied Computation Lab at Princeton University, to represent an existing timber structure built according to conventional North American stick frame construction practices. A multi-directed graph data structure, representing structural member connectivity and support hierarchy, is then coupled with a breadth-first search algorithm to plan potential scaffold-free robotic disassembly sequences given a member removal target. In parallel, computer vision is integrated and implemented through the robotic setup to create an accurate as-built point cloud scan of the whole structure. This as-built information is then used to inform the evaluation of potential robotic sequences from the point of view of robotic reachability and structural performance. This work-in-progress paper first presents a high-level overview of the various components in this workflow, followed by its demonstration in planning the removal of a specific member in the prototype structure. Upcoming project developments will include the planning, and physical demonstration, of more complex disassembly sequences, coupled with reassembly and reuse of the removed members for various regions of the prototype structure.

INTRODUCTION

Construction and demolition processes continue to be among the largest contributors to our contemporary waste crisis (US EPA 2018). Among the many material systems used in North American building practices, conventional timber frame construction stands out as not only the most pervasive and ubiquitous, but also the most readily discarded (O'Brien et al. 2006; Diyamandoglu and Fortuna 2015). We address this problem by re-situating timber buildings as material depots, as a site of valuable material resources that can be utilized as part of a circular economy framework (Zimmann 2016). Identifying and cataloging existing building stock privileges the flow of material upstream on the construction site rather than downstream to the recycling and waste industry (Garcia et al. 2021).

Significant research activity has centered on creating models to better quantify the environmental benefits of material circularity and reuse potential of existing building stock (Cottafava and Ritzen 2021; Eberhardt et al. 2021). But there is need for further physical deconstruction and reassembly projects that combine existing buildings with modern digital fabrication tools (Brütting et al. 2019, 2021). With *ZeroWaste*, we aim to address this research gap by integrating 3D imaging technology with a cooperative industrial robotic fabrication setup, which can then be utilized for both information gathering and the physical disassembly and reuse of conventional timber frame structures.

Cooperative Robotic Assembly and Disassembly

Robots have been used in the design and construction industry for over forty years (Bock 2007). While initial developments focused on automating single human tasks (Bock and Linner 2016), in the last decades, researchers have begun using robots to enhance constructive work and expand the design space by making use of their specific capabilities, such as precise movement and accurate spatial placement of components (Gramazio and Kohler 2008). In a cooperative robotic setup, multiple robots are specifically sequenced to achieve outcomes that would not be possible with a single robot (Parascho et al. 2018). For example, geometrically complex structures can be assembled without temporary scaffolding when alternating the robotic placement of material and support of the structure during fabrication (Bruun et al. 2020, 2021; Han et al. 2020; Parascho et al. 2020, 2021). In *ZeroWaste*, we build on specific concepts from our most recent work on the scaffold-free cooperative robotic assembly and disassembly of a timber space frame structure (Bruun et al. 2022) and more conceptually on prior research about the robotic assembly of bespoke timber modules (Thoma et al., 2018). Thus, extending the capabilities of industrial robots beyond their traditional role in assembly.

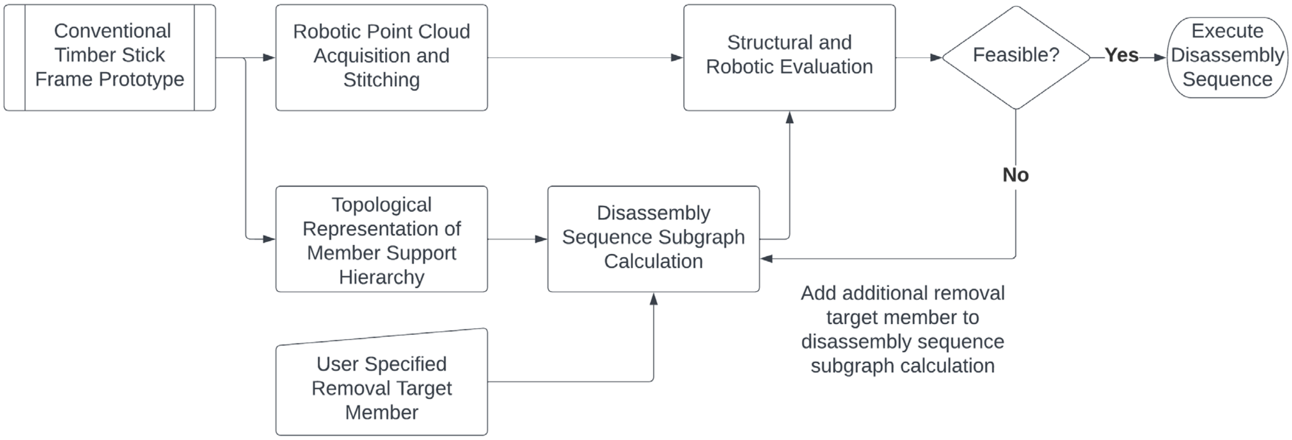
ZeroWaste Project Description

The overall project is to develop a computational approach for determining how multiple industrial robotic arms should be sequenced for the scaffold-free disassembly and reconfiguration of an existing timber structure. Specifically, the goal is to plan a multi-robot sequence that leverages the robots as temporarily support to maintain stability of the structure during all stages of fabrication. While an assembly process can be completely pre-planned and simply executed by robots, for disassembly the robots take on the additional role of information gatherers. In *ZeroWaste*, the two robotic arms that are on tracks are first used to collect data and create a complete as-built point cloud of an unknown structure; this as-built information is then used in the computational workflow for planning a feasible robotic disassembly and reassembly sequence.

A timber structure prototype is used as a stand-in for an unknown existing structure built according to typical North American timber stick frame construction practices. While in this paper the robotic sequences are planned with this specific prototype structure in mind, the approaches developed are intended to be generic and thus transferable to similar discrete element structures. The complete project involves developing a workflow and implementing it in the planning of the robotic fabrication for the following four distinct phases:

- Phase 1: Removal of a simulated "damaged" member in the structure.
- Phase 2: Disassembly and partial reassembly of a region of the structure.
- Phase 3: Disassembly and one-to-one member reassembly of a single wall in the structure.
- Phase 4: Disassembly and partial reassembly of the whole structure.

This work-in-progress paper focuses on a high-level description of the generic computational workflow (Figure 2) and describe how it was implemented specifically for Phase 1. The approach is to use a support hierarchy topological representation of the structure to calculate possible stable disassembly sequences, after which a sequence is selected based on structural performance and robotic feasibility criteria evaluated using the as-built point cloud data. The subsequent phases, which will be presented in a future publication, increase in planning complexity but build on the methods described in this paper in the context of Phase 1.



2

METHODS

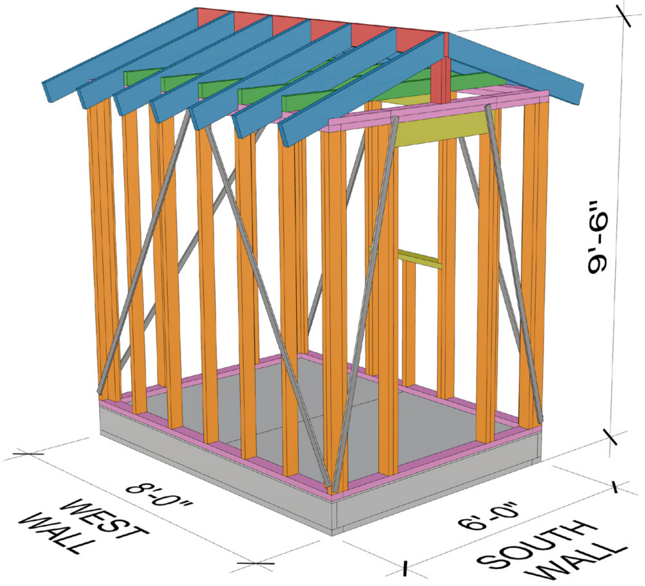
Description of Timber Structure Prototype

A life-sized timber structure, built according to conventional American stick frame construction practices, serves as the experimental prototype for the computational methods presented in this paper. The as-built structure is shown in Figure 3 and 4, and measures 8 ft by 6 ft (~2.4 m by 1.8 m) in plan with a height of 9.6 ft (~2.9 m) built from SPF dimensional lumber. Members of the same type are grouped by color as shown in Figure 4. The following types of members are present in the structure: roof girder (x1, red), roof post (x2, brown), roof rafter (x14, blue), ceiling joint (x5, green), top plate (x4, pink), wall studs (x32, orange), header beams (x3, yellow), sheathing diagonals (x7, grey), bottom plate/floor (x4, black). These colors also be used to distinguish the different members in the support hierarchy graph representation (Figure 8). Wall sheathing is represented as diagonal members, which provide the necessary shear stiffness to the structure.

As-Built Structure Point Cloud

The first step in the disassembly sequence planning process is generating an accurate as-built digital representation of the structure. The prototype in the project is meant to represent an existing building for which detailed geometric information might not be available. In addition, as-built conditions might differ geometrically from what was planned even for known structures. Thus, design renders are not sufficiently accurate for planning robotic paths, support sequencing, and where to send the robots to grip members.

3



4

2 High-level workflow for Phase 1 of the *ZeroWaste* project corresponding to the different topics discussed in the Methods section

3 Photo of the conventional stick frame prototype structure in the Embodied Computation Lab at Princeton University

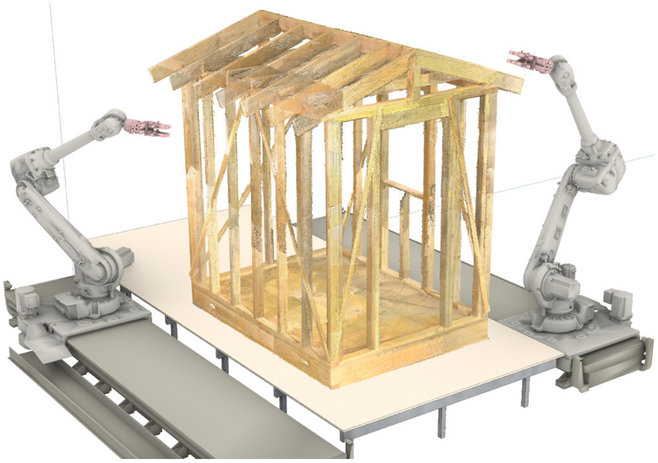
4 Rendering of timber structure where the various colors indicate the different types of members

The two IRB4600 robots (40 kg payload, 2.55 m reach) are each equipped with a Zivid 3D structured light camera with a spatial resolution of 0.39 mm at 700 mm distance (Zivid AS 2021). A point cloud of the full structure is created by moving the robots to various positions in space and capturing 3D images. These images are then transformed to the same coordinate system, stitched together using in-house developed scripts implementing the Zivid API, and downsampled to remove duplicate points. The transformation of a point cloud in the camera coordinate frame (P_{Object_Camera}) to a point cloud in the world0 (e.g., the 0 location in the CAD model) coordinate frame (P_{Object_World0}) is described as: $P_{Object\_World0} = H_3 \times H_2 \times H_1 \times P_{Object\_Camera}$

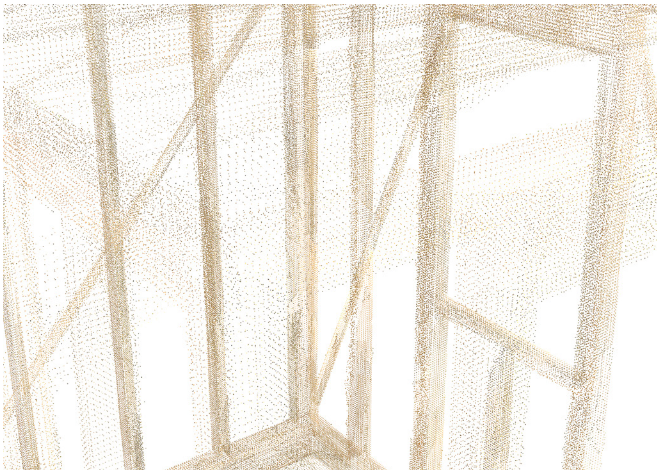
Where the 4x4 transformation matrices are the following:

- H_1: from robot tool center point (TCP) to camera location, calculated from the calibration routine.
- H_2: from robot base to the robot TCP, queried as a positional frame using the COMPAS RRC API (Fleischmann 2020).
- H_3: from World0 to the work object (WOBJ), user defined.

Figure 5 and 6 show the results of the point cloud scan of the structure, which is a combination of 100 separate image captures with Robot 1 (right), and 60 image captures with Robot 2 (left). A voxel size of 10 mm was used to downsample the stitched together point cloud, which resulted in a coarse model with approximately 0.5 million points. Additional point cloud fidelity can be preserved by reducing the voxel size, but this was not necessary at this stage when planning robotic paths.



5



6

5 Point cloud of the as-built timber structure stitched together from multiple captures using two robots and transformed to the World0 coordinate frame

6 Zoomed in perspective of stitched together point cloud showing the low resolution downsampling based on a 10 mm voxel size

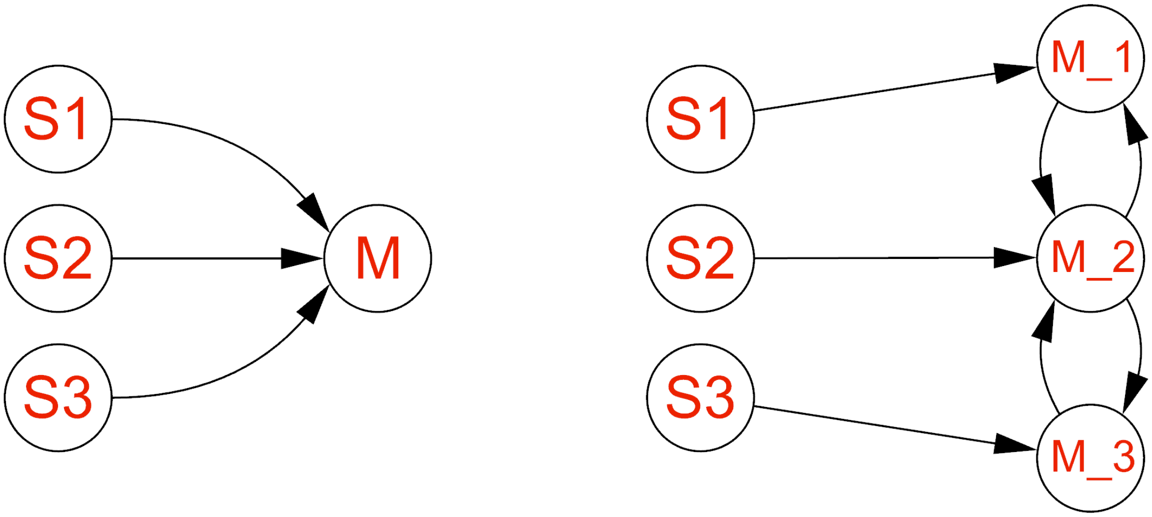
Topological Representation of Member Support Hierarchy

Planning a stable and feasible disassembly sequence requires information about how the members in a structure are connected and supported by each other. A way to represent the connectivity and support hierarchy in a structure is through a multi directed graph (multidigraph) data structure (Valiente 2021). The vertices in the graph represent individual members, and the edges represent connections between members, with outgoing edges indicating the direction of support (e.g., S members are supported by the M member in Figure 7). When a member has multiple connection locations, it can be better represented by dividing it into its constitutive submembers. Vertices representing pieces of the same member are joined with two parallel but opposite edges to indicate the mutual support relationship between them (i.e., this is considered a fixed connection). An example of this is shown in Figure 7.

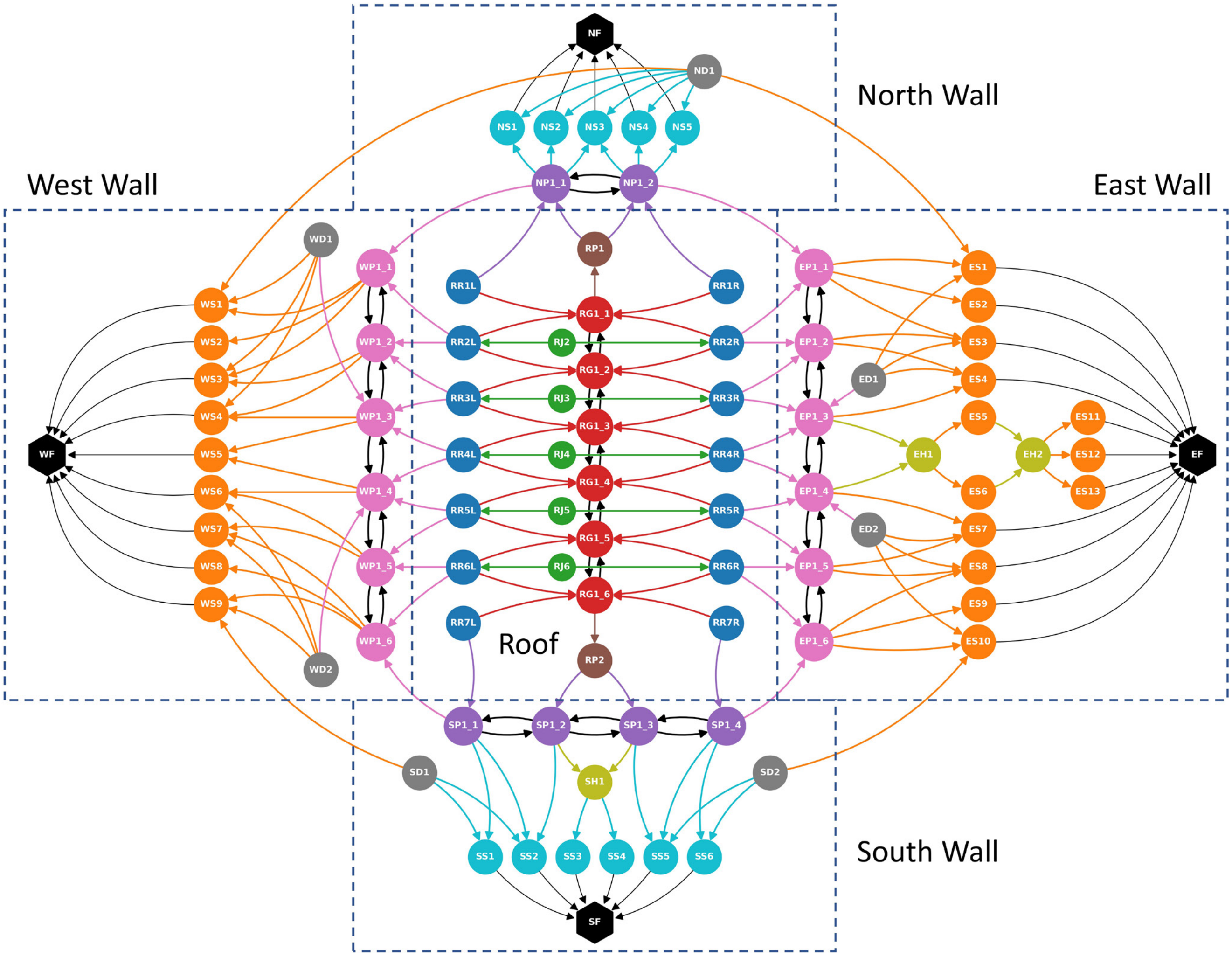
The graph of the full prototype structure is built manually and shown in Figure 8, where the colors of the vertices correspond to the member color scheme in Figure 4. For clarity, the structure is divided into five regions representing the roof and the four walls. The vertex naming convention is as follows AB#_$:

- A: The first digit of each vertex indicating if it is part of the roof (R) or one of the four walls (N, S, E, W). In Figure 5, the South wall is the short side closest to the camera.
- B: The second letter represents the type of member; roof girder (G), roof post (P), roof rafter (R), ceiling joint (J), top plate (P), wall studs (S), header beams (H), sheathing diagonals (D), foundation support (F).
- #: The third digit is used to number a unique member of a particular type.
- $: The fourth digit is used to indicate a unique subcomponent of a single member.

The graph terminates at the foundation supports, which are shown as hexagonal vertices and represent a bearing support between the bottom plate of each wall and the ground.



7



8

7 Directed edges show that members S1, S2, S3 are supported by member M. This support member can also be shown subdivided into its constituent submembers (M1, M2, M3) that are connected with parallel and opposite edges to represent a fixed connection.

8 The connection hierarchy in the discrete element timber prototype structure is represented as a multidirected graph with outgoing edges indicating the direction of support. Vertices correspond to unique members or submembers in the structure and are organized into five regions (North, South West, East Walls, and the Roof).

Disassembly Sequence Subgraph

Given a target member for removal, a subgraph representing all the members in the structure that need to be removed and supported along the way is calculated through an algorithmic operation on the full support member hierarchy graph. The algorithm implemented is a modified breadth-first search, which explores regions in the graph adjacent to the member specified for removal (Valiente 2021). The logic is that if a member is supporting another member (i.e., has an incoming edge), then this supported member must first be removed or temporarily held in place by a robot before the supporting member can be safely removed.

The breadth-first search finishes when the queue of vertices to check by the algorithm is empty, which occurs before traversing the full graph since certain conditions result in an “end vertex” (i.e., its neighbors are not checked). For example, if a vertex only has outgoing edges, the member it represents can be removed without impacting any other parts of the structure. Conversely, if a vertex only has incoming edges, then it is a support vertex. There is a more complex end condition for a vertex representing a submember. When such a vertex is reached, it can trigger the end condition if the submember can be cut from its parent member while ensuring that the stability of the parent member is maintained (i.e., has at least two support points).

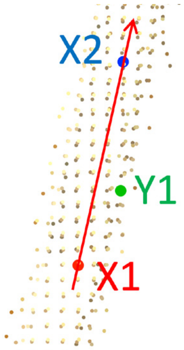
Structural and Robotic Evaluation of Disassembly Sequence

The disassembly subgraph calculated from the member support hierarchy graph can be thought of as a high-level plan for the removal of a member. However, additional checks related to structural stability and robotic reachability must be performed to verify that this sequence is feasible. This is done through two parallel processes: (1) a parametric finite element (FE) study of the structure in Rhino/Grasshopper using Karamba3D (Preisinger 2013), and a robotic path planning validation using the COMPAS and COMPAS FAB package with a ROS backend (Rust et al. 2018; Mele et al. 2017).

The point cloud of the as-built structure is used to build a finite element beam model of the structure, based on the centerline of the members identified in the point cloud. Working with this model in a parametric environment allows for a disassembly sequence to be fed directly into the analysis pipeline, by sequentially turning members off as they are removed from the structure. Temporary robotic support on the structure is represented as an additional pin support that can be assigned by the user.

The as-built structure point cloud is also used to test the robotic reachability and path planning related to a calculated disassembly sequence. Sets of three points are sampled from different locations along a member and are used to construct a plane in space where a robot would be sent to pick the member. Figures 9 to 11 show an example of this process. The X1 point represents the center of the plane, with the *X*-axis orientation defined as a vector between X1 and X2. Y1 is the third and final point anywhere on the surface of the member used to define the plane. These pick locations on the various members are then checked while simulating the disassembly sequence to see if a collision-free path is possible to reach them. If this path-planning check returns that no path is possible, either because of collisions with the rest of the structure or with the other robots, then the original disassembly sequence will require updating. These updates consist of removing additional members in the structure or moving the robots into less obstructive positions.

9

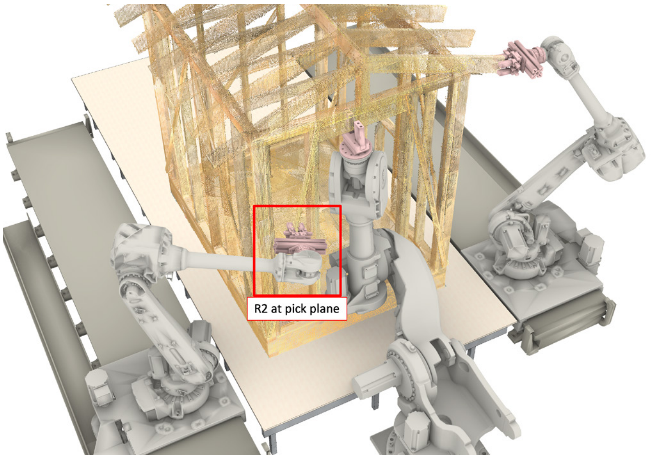


10

9 Front elevation of the structure point cloud with three points on the surface of a diagonal member highlighted

10 Sets of three points (X1, X2, Y1) are sampled from the point cloud of a member and are used to define the location and orientation of a robotic pick plane centered at X1

11 Each pick plane is checked to have a collision-free robotic path and final configuration kinematically possible to reach and grab the corresponding member



11

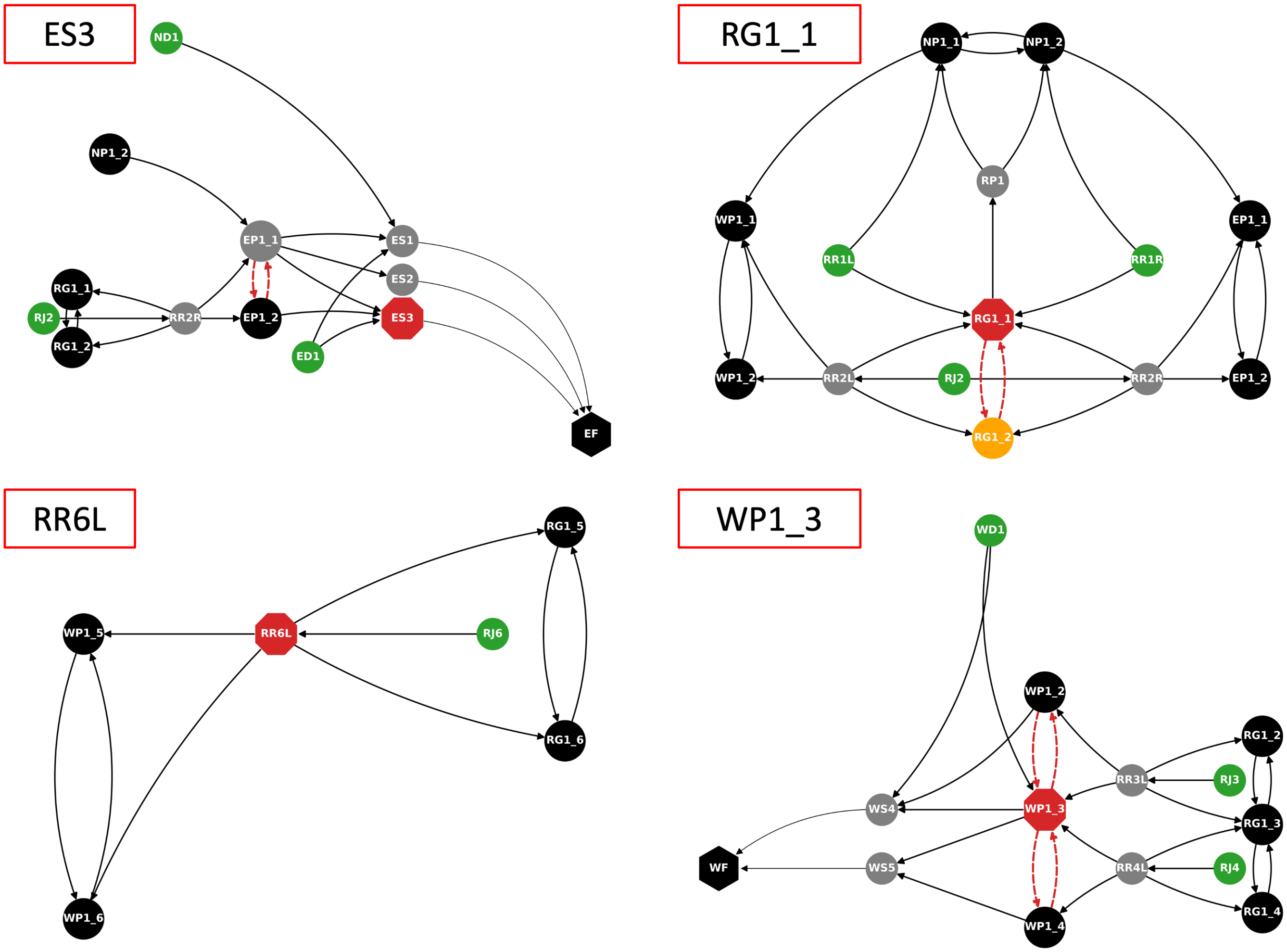
RESULTS AND DISCUSSION

Examples of Disassembly Subgraphs

Figure 12 shows several subgraphs generated from the overall member hierarchy graph with different member removal targets as inputs. The vertices here are highlighted to indicate different types of members in the structure:

- Red: specified member removal target
- Grey: regular member
- Black: support or a submember that is adequately supported in this sequence
- Green: start member (i.e., no member is supported on it
- Yellow: submember that may require additional support in this sequence (i.e., not adequately supported)

In addition, parallel edges between submember are highlighted in red if the member must be cut at this location during the process of disassembly.



12 Example disassembly sequence subgraphs calculated with different member removal targets (red) specified as inputs: east face stud #3 (ES3), roof girder subcomponent #1 (RG1_1), roof rafter beam #6 (RR6L), and west top plate subcomponent #3 (WP1_3). These subgraphs represent all the members in the structure that are affected in the process of removing the target member.

Detailed Disassembly Planning for Member SS1

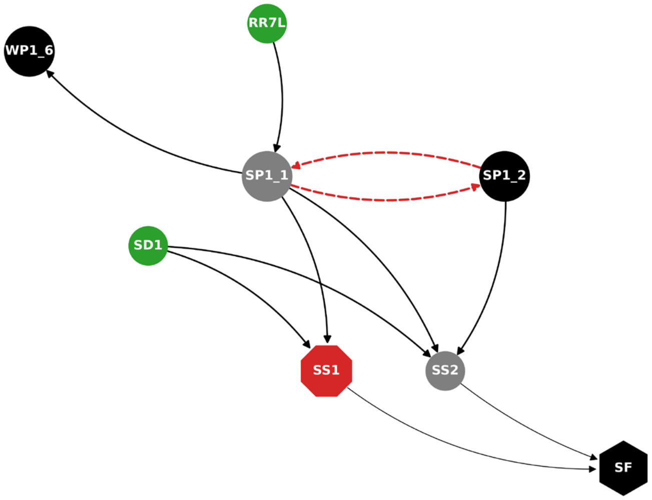
Member SS1 (South Wall, Stud #1) is chosen to be removed as part of Phase 1 of the *ZeroWaste* project. The process of calculating a disassembly sequence is meant to simulate the process of planning the removal of a potentially damaged member in a timber stick frame structure. Figure 13 show the disassembly subgraph calculated from the support hierarchy topological representation with the numerical approach described in the previous sections. The physical members that the graph represents are shown in Figure 14.

13 The calculated subgraph representing all the members part of a feasible disassembly sequence for member SS1 (South Wall Stud #1)

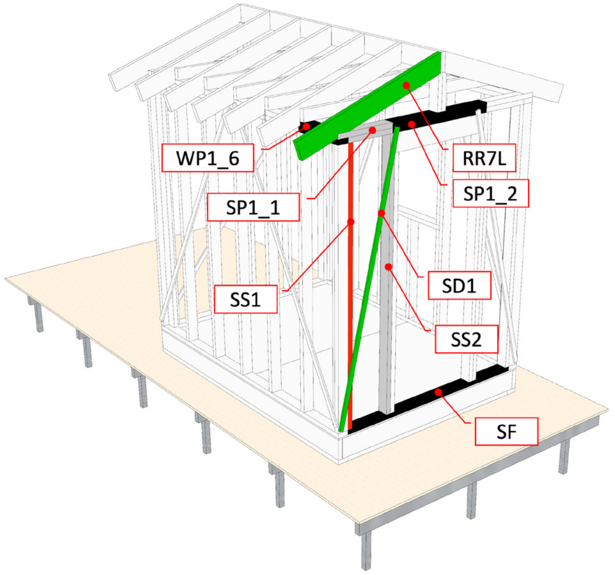
14 The members affected in the removal of member SS1 highlighted based on their connectivity and labelled in the rendering of the prototype structure

15 Aggregate disassembly subgraph when including member WS9 as a disassembly target

16 Aggregate disassembly subgraph when including member SS3 as a disassembly target

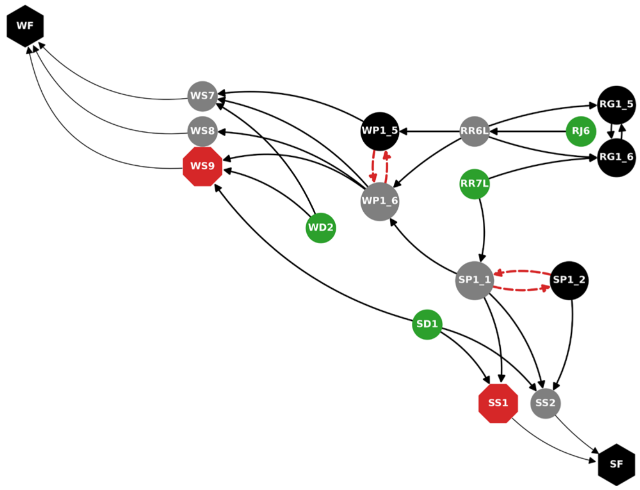


13

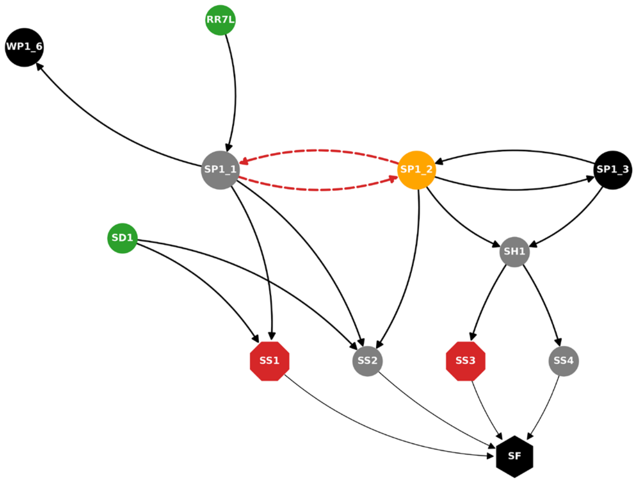


14

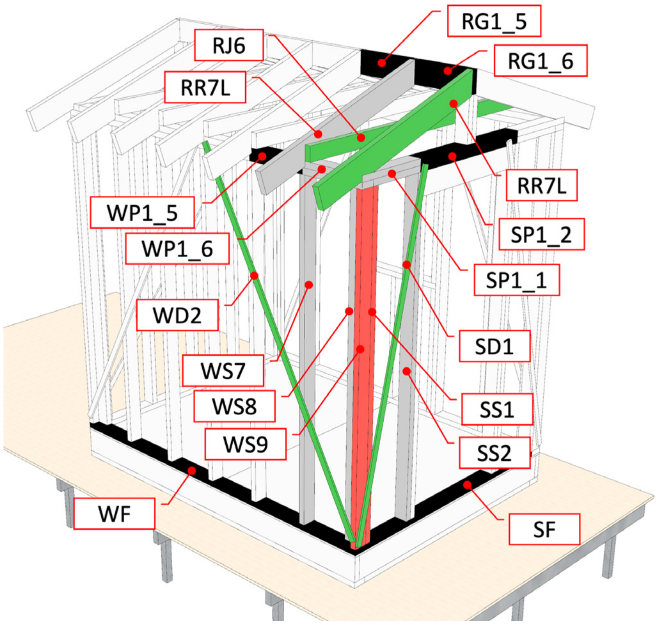
Structural and robotic kinematic evaluation of this sequence follow, which reveal that while the sequence is structurally feasible (i.e., can be executed without compromising stability) the robot is not able to reach member SS1 without colliding with either member WS9 or SS3. The subgraph for the removal of either of these members can be combined with the original SS1 subgraph to create two an aggregate disassembly sequences shown in Figure 15 and 16 respectively. While both sequences are feasible, the option with SS3 results in member SP1_2 not being adequately supported at the conclusion of this process (i.e., less than two supports remaining). Meanwhile, choosing the option with WS9 requires the removal of more members (12 vs. 9), but results in a structure that is self-stable at its termination. The structure at the end of the disassembly sequence is shown in Figure 17 and 18, with the eight individual steps in the cooperative robotic disassembly sequence shown in Figure 19.



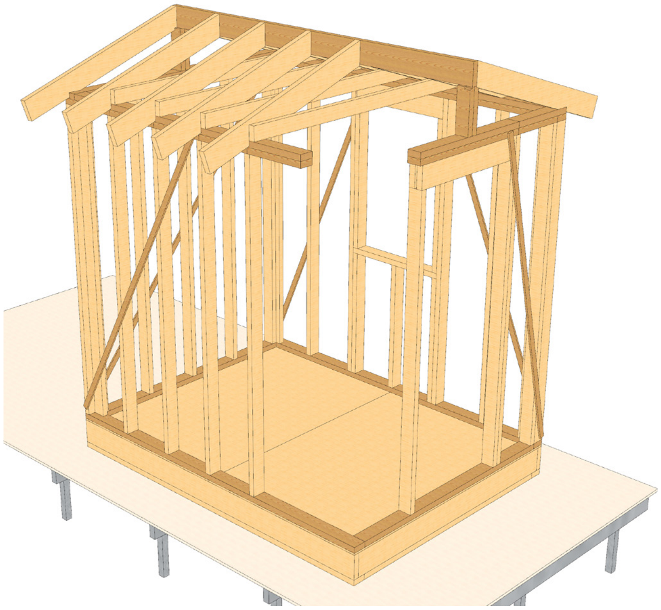
15



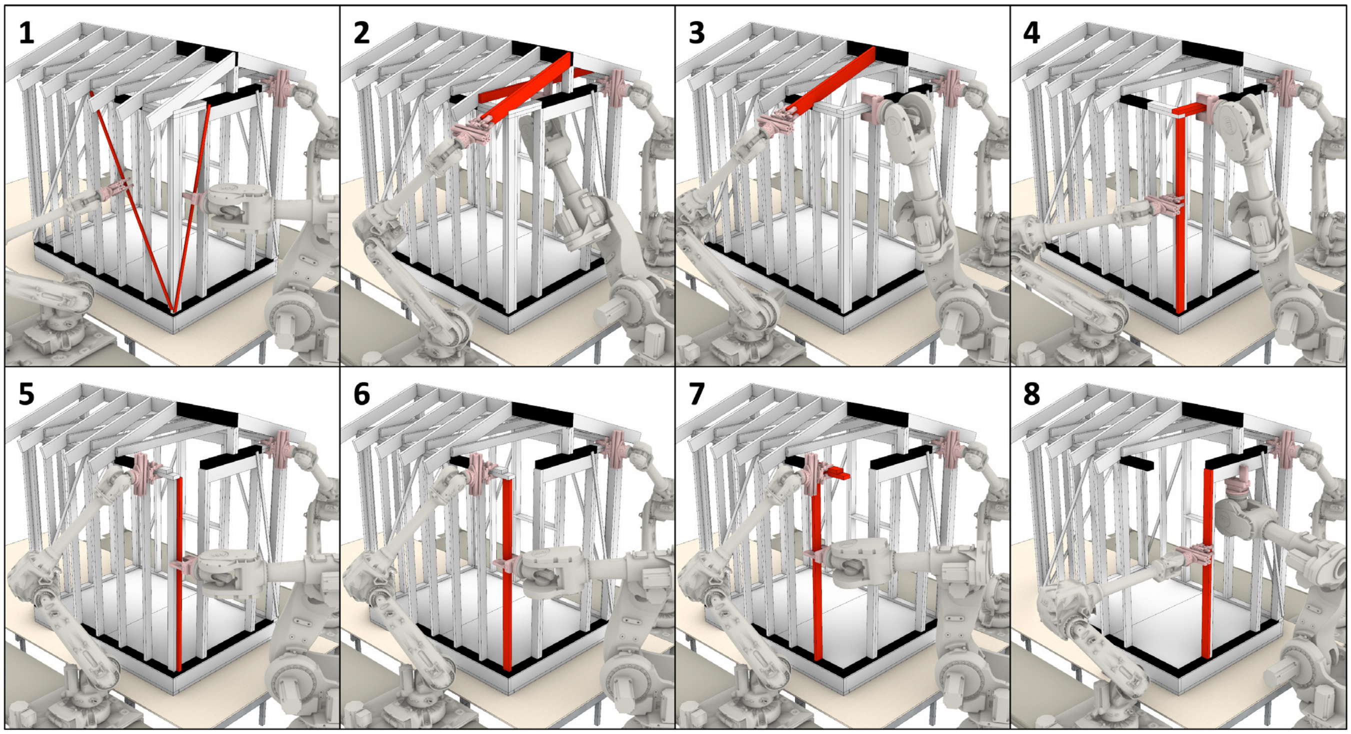
16



17



18



19

17 The physical members represented in the disassembly subgraph (Figure 15) calculated for members SS1 and WS9 as removal targets

18 The remaining part of the prototype timber structure after the disassembly sequence for members SS1 and WS9 is executed

19 The eight steps required in the cooperative robotic disassembly sequence for the removal of members SS1 and WS9. In each step the members to be removed are shown in red: (1) SD1 & WD2, (2) RR7L & RJ6, (3) RR6L, (4) SP1_1 & WS9, (5) SS1, (6) WS8, (7) WP1_6 & WS7, (8) SS2. Black members are end vertices or supports.

CONCLUSION

The *ZeroWaste* project is about creating a computational workflow for planning the scaffold-free cooperative robotic disassembly and reassembly of existing timber structures as a means for rethinking material circulation in the building industry. This work-in-progress paper focused on aspects of the disassembly planning, and presented the first steps in the development of this process, with a focus on explaining the information gathering methods for an unknown timber structure. We demonstrated how computer vision integrated with a robotic setup can be used to create an accurate as-built representation of an existing timber structure. This information, coupled with a topological representation of the member support hierarchy, was then used to compute various robotic disassembly sequences, and evaluate their robotic and structural feasibility. These methods were demonstrated in the planning of a feasible cooperative robotic disassembly sequence for the removal of a single member as part of Phase 1 of the project. The next project developments will involve the planning and physical demonstration of more complex disassembly sequences, coupled with reassembly of the removed members, for larger portions of the prototype structure (i.e., Phases 2-4).

ACKNOWLEDGMENTS

We would like to thank the following people for their help at various stages throughout the project: Chris Myefski, Chase Galis, Ian Ting, and John Mikesh. In addition, we would like to acknowledge the industry support from Zivid, in the form of reduced pricing for their high-end 3D color cameras. The project is funded in part by Princeton's Campus as a Lab fund and the National Science Foundation (Grant CMMI-ECI 2122271).

REFERENCES

Bock, Thomas. 2007. "Construction Robotics." *Autonomous Robots* 22 (3): 201–9. https://doi.org/10.1007/s10514-006-9008-5.

Bock, Thomas, and Thomas Linner. 2016. *Construction Robots: Elementary Technologies and Single-Task Construction Robots*, vol. 4. Cambridge, UK: Cambridge University Press.

Bruun, Edvard P. G., Sigrid Adriaenssens, and Stefana Parascho. 2022. "Structural Rigidity Theory Applied to the Scaffold-Free (Dis) Assembly of Space Frames Using Cooperative Robotics." *Automation in Construction* 141 (June): 104405. https://doi.org/10.1016/j.autcon.2022.104405.

Bruun, Edvard P. G., Rafael Pastrana, Vittorio Paris, Alessandro Beghini, Attilio Pizzigoni, Stefana Parascho, and Sigrid Adriaenssens. 2021. "Three Cooperative Robotic Fabrication Methods for the Scaffold-Free Construction of a Masonry Arch." A*utomation in Construction* 129 (September): 103803. https://doi.org/10.1016/j.autcon.2021.103803.

Bruun, Edvard P. G., Ian Ting, Sigrid Adriaenssens, and Stefana Parascho. 2020. "Human–Robot Collaboration: A Fabrication Framework for the Sequential Design and Construction of Unplanned Spatial Structures." *Digital Creativity* 31 (4): 320–336. https://doi.org/10.1080/14626268.2020.1845214.

Brütting, Jan, Joseph Desruelle, Gennaro Senatore, and Corentin Fivet. 2019. "Design of Truss Structures through Reuse." *Structures* 18 (April): 128–37. https://doi.org/10.1016/j.istruc.2018.11.006.

Brütting, Jan, Gennaro Senatore, and Corentin Fivet. 2021. "Design and Fabrication of a Reusable Kit of Parts for Diverse Structures." *Automation in Construction* 125 (May): 103614. https://doi.org/10.1016/j.autcon.2021.103614.

Cottafava, Dario, and Michiel Ritzen. 2021. "Circularity Indicator for Residential Buildings: Addressing the Gap between Embodied Impacts and Design Aspects." *Resources, Conservation and Recycling* 164 (January): 105120. https://doi.org/10.1016/j.resconrec.2020.105120.

Diyamandoglu, Vasil, and Lorena M. Fortuna. 2015. "Deconstruction of Wood-Framed Houses: Material Recovery and Environmental Impact." *Resources, Conservation and Recycling* 100 (July): 21–30. https://doi.org/10.1016/j.resconrec.2015.04.006.

Eberhardt, Leonora, Julie Rønholt, Morten Birkved, and Harpa Birgisdottir. 2021. "Circular Economy Potential within the Building Stock; Mapping the Embodied Greenhouse Gas Emissions of Four Danish Examples." *Journal of Building Engineering* 33 (January): 101845. https://doi.org/10.1016/j.jobe.2020.101845.

Fleischmann, Philippe, Gonzalo Casas, and Michael Lyrenmann. 2020. "COMPAS RRC: Online Control for ABB Robots over a Simple-to-Use Python Interface." July 2020. https://doi.org/10.5281/zenodo.4639418.

Garcia, Anna Batalle, Irem Yagmur Cebeci, Roberto Vargas Calvo, and Matthew Gordon. 2021. "Material (Data) Intelligence - Towards a Circular Building Environment." In *Proceedings of the 26th International*

Conference of the Association for Computer-Aided Architectural Design Research in Asia, vol. 1. 361–70. http://papers.cumincad.org/cgi-bin/works/paper/caadria2021_088.

Gramazio, Fabio, and Matthias Kohler. 2008. *Digital Materiality in Architecture*, 1st ed. Baden: Lars Muller.

Han, Isla Xi, Edvard P. G. Bruun, Stuart Marsh, Sigrid Adriaenssens, and Stefana Parascho. 2020. "From Concept to Construction: A Transferable Design and Robotic Fabrication Method for a Building-Scale Vault." In *ACADIA '20: Distributed Proximities; Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture*. Online. 614–623. http://papers.cumincad.org/cgi-bin/works/Show?acadia20_614.

Mele, Tom Van, Andrew Liew, Tomas Mendéz Echenagucia, and Matthias Rippmann. 2017. "COMPAS: A Framework for Computational Research in Architecture and Structures." COMPAS. 2017. https://compas-dev.github.io/.

O'Brien, Elizabeth, Bradley Guy, and Angela Stephenson Lindner. 2006. "Life Cycle Analysis of the Deconstruction of Military Barracks: Ft. McClellan, Anniston, AL." *Journal of Green Building* 1 (4): 166–83. https://doi.org/10.3992/jgb.1.4.166.

Parascho, Stefana, Isla Xi Han, Alessandro Beghini, Masaaki Miki, Samantha Walker, Edvard P. G. Bruun, and Sigrid Adriaenssens. 2021. "LightVault: A Design and Robotic Fabrication Method for Complex Masonry Structures." In *Advances in Architectural Geometry 2020*. Paris, France: Presses des Ponts. 350–75. https://thinkshell.fr/wp-content/uploads/2019/10/AAG2020_18_Parascho.pdf.

Parascho, Stefana, Isla Xi Han, Samantha Walker, Alessandro Beghini, Edvard P. G. Bruun, and Sigrid Adriaenssens. 2020. "Robotic Vault: A Cooperative Robotic Assembly Method for Brick Vault Construction." *Construction Robotics* 4 (3): 117–26. https://doi.org/10.1007/s41693-020-00041-w.

Parascho, Stefana, Thomas Kohlhammer, Stelian Coros, Fabio Gramazio, and Matthias Kohler. 2018. "Computational Design of Robotically Assembled Spatial Structures: A Sequence Based Method for the Generation and Evaluation of Structures Fabricated with Cooperating Robots." In A*dvances in Architectural Geometry 2018*. Gothenburg, Sweden: Klein Publishing GmbH. 112–139. https://research.chalmers.se/en/publication/504188.

Preisinger, Clemens. 2013. "Linking Structure and Parametric Geometry." *Architectural Design* 83 (2): 110–13. https://doi.org/10.1002/ad.1564.

Rust, R., G. Casas, S. Parascho, D. Jenny, K. Dörfler, M. Helmreich, A. Gandia, Z. Ma, I. Ariza, and M. Pacher. 2018. "COMPAS FAB: Robotic Fabrication Package for the COMPAS Framework." COMPAS Fab. 2018. https://github.com/compas-dev/compas_fab/.

Thoma, Andreas, Arash Adel, Matthias Helmreich, Thomas Wehrle, Fabio Gramazio, and Matthias Kohler. 2018. "Robotic Fabrication of Bespoke Timber Frame Modules." In *Robotic Fabrication in Architecture, Art and Design 2018*. Zurich: Springer International Publishing. 447–458. https://doi.org/10.1007/978-3-319-92294-2_34.

US EPA (United States Environmental Protection Agency). 2018. "Construction and Demolition Debris Generation in the United States, 2015." Office of Resource Conservation and Recovery. Accessed September 2, 2022. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/studies-summary-tables-and-data-related.

Valiente, Gabriel. 2021. *Algorithms on Trees and Graphs: With Python Code*, 2nd ed. Cham: Springer.

Zimmann, Rainer, Harriet O'Brien, Josef Hargrave, and Marcus Morrell. 2016. "The Circular Economy in the Built Environment." Arup. Accessed September 2, 2022. https://www.arup.com/perspectives/publications/research/section/circular-economy-in-the-built-environment.

Zivid AS. 2021. "Zivid Two." Technical Specifications. Oslo, Norway. Accessed September 2, 2022. https://www.zivid.com/zivid-two?hsLang=en.

IMAGE CREDITS

All drawings and images by the authors.

Edvard P. G. Bruun is a PhD Candidate in the Form Finding Lab in the Civil and Environmental Engineering Department at Princeton University. Before starting his PhD, he worked as a structural engineer at Arup. His current research interests lie in exploring how multiple industrial robotic arms can be sequenced cooperatively when applied to the dis(assembly) of discrete-element structures. He develops approaches that leverage the multi-functionality of robotic setups to design aesthetic and efficient structures that can be (dis)assembled while preserving their stability without the need for any external scaffolding.

Erin Besler is an Assistant Professor of Architecture at Princeton University and cofounder of Besler & Sons, a design studio based in central New Jersey. They were named 2019 United States Artists Fellows in Architecture & Design. Their work has been exhibited at venues internationally, including the MAK Center for Art and Architecture, Chicago Architecture Biennial, and Shenzhen and Hong Kong Bi-City Biennale of Architecture/Urbanism. Recently, they were awarded a grant from the Graham Foundation for their debut book *Best Practices*. Erin's work is characterized by a particular interest in construction technologies, social media, and other platforms for producing and sharing content, where interactions rely less on expertise and more on ubiquity.

Sigrid Adriaenssens directs the Form Finding Lab at Princeton University, where she also teaches courses on (non-)linear mechanics and design of structures and the integration of engineering and arts. Her research interests lie in the mechanics of large-span structural surfaces under extreme loading and under construction. She works on advanced analytical formulations, numerical form finding and optimization approaches, fluid/structure interaction and machine learning models algorithms to open new avenues for accelerated discoveries and automated optimal designs. In 2021, she was named Fellow of the ASCE Structural Engineering Institute, elected IASS vice-president, received the DigitalFUTURES Matthias Rippmann and the Pioneers's Award.

Stefana Parascho is a researcher, architect, and educator whose work combines architecture, digital fabrication and computational design. She is currently Assistant Professor at EPFL where she founded the Lab for Creative Computation (CRCL). Through her research, she has explored multi-robotic fabrication methods and their relationship to architectural design. Her goal is to strengthen the connection between design, structure, and fabrication, and boost the interdisciplinary nature of architecture. Before joining EPFL, she was Assistant Professor at Princeton University. She completed her doctorate in 2019 at ETH Zurich and received her Diploma in Architectural Engineering from the University of Stuttgart.