Advancing Sustainable Approaches in Architecture by Means of Design-to-Robotic-Production

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Abstract

The construction sector accounts for about 40% of material-, energy- and process-related carbon dioxide (CO2) emissions [1], which can be reduced by introducing data-driven Circular Economy (CE) approaches [2]. For instance, Design-to-Robotic-Production (D2RP) methods developed in the Robotic building lab, at Technical University (TU) Delft are embedding data-driven systems into building processes. Their potential to contribute to sustainability through increased material-, process-, and energy-efficiency has been explored in several case studies that are presented in this paper. The assumption is that by using these methods and reclaimed wood to minimize demand for new resources and reduce deforestation along the way, CO2 emissions can be considerably reduced.

Keywords

Architecture, building construction, CO2, circular- and AI-supported robotic approaches

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1 Link to IEA report:
https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

2 Links to Springer volumes edited by Bier (2018) and Morel and Bier (2023):
https://link.springer.com/book/10.1007/978-3-319-70866-9 and
https://link.springer.com/book/9783031141591

1 Introduction

In the last decade, data-driven, and in particular, robotic applications in architecture and building construction have increasingly proven their potential for contributing to sustainability through increased material, process, and energy-efficiency (Ashby, 2024; Bier, 2018). When integrated with Circular Economy (CE) approaches additional carbon dioxide (CO_2) reduction is to be expected (Dokter et al., 2021).

Design-to-Robotic-Production (D2RP) methods presented in this paper as part of a larger Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) framework developed at Technical University (TU) Delft integrate data-driven design involving performance optimization techniques to maximize functional-, structural-, material-, and energy-efficiency with CE approaches that rely on the reuse of materials while taking life-cycles into account. Furthermore, they increasingly take advantage of Artificial Intelligence (AI) in various stages of the design to construction process (Bier et al., 2022).

2 Design-to-Robotic-Production

D2RP efficiently links computational design with robotic production. It involves subtractive and additive techniques such as cutting and milling into materials such as plastic, wood, etc. and robotic 3D-printing with materials such as clay, plastic, etc., respectively (Bier, 2018; Bier et al., 2020). When equipped with various end-effectors robotic arms are versatile and in combination with Machine Learning (ML) models that accurately simulate the process and predict how processes evolve over time, and optimal settings can be identified (Peters et al., 2011) to optimize energy consumption and thereby reduce material use and processing time.

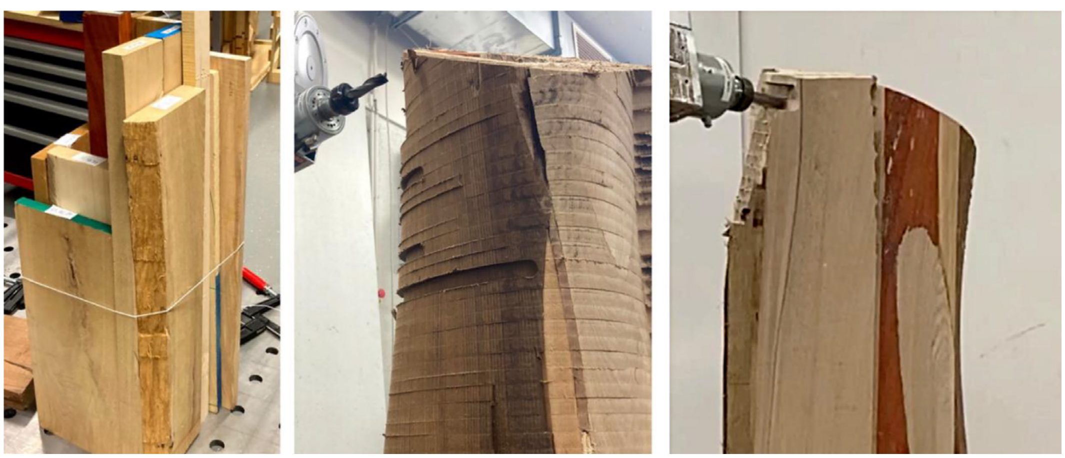

FIGURE 1 Packed, glued (left) and milled (middle and right) reclaimed wood boards serving as curvilinear beams for a larger structure.

3 Subtractive D2RP

Subtractive D2RP methods were advanced at TU Delft amongst others in a case study involving reclaimed wood. The overall goal was to demonstrate the potential of robotically processed reclaimed materials in architecture (Fig. 1-3) to not only improve efficiency and reduce CO2 but also create aesthetically pleasing artefacts.

The use of circular wood has been explored in collaboration with the University of Applied Science (UAS) Amsterdam. It involved the processing of reclaimed wood by laminating reclaimed wood boards into a larger component, which was robotically milled into topologically optimized curvilinear beams as part of a larger structure[3]. The combination of various wood boards from various types of wood resulted in an aesthetically pleasing pattern of alternating darker and lighter wood (Fig. 1) due to the randomly packed wood boards.

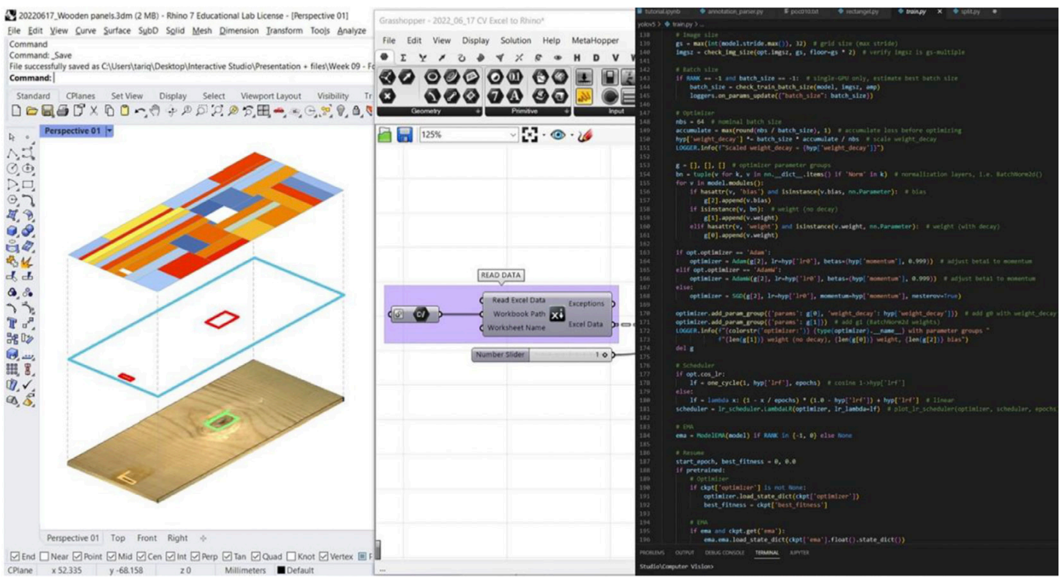

FIGURE 2 ML-supported processing of reclaimed wood panels.

The lamination of reclaimed wood boards in this initial study could have profited from the ML- supported approaches involving Computer Vision (CV) that was developed in a later study in collaboration with the AiDAPT lab at TU Delft. The CV was employed to identify defects in the wood with the goal to demarcate and remove them in order to ensure the structural integrity of the to-be-built structure. The defect recognition using images of wooden boards relied on a trained model that identified the size of the board and demarcated the defects (Fig. 2). These were used within Grasshopper Rhino [4], to generate cutting patterns to remove respective defects. The obtained dataset consisting of 4000 wood boards images with visible defects was pre-labelled as part of another dataset in Kaggle[5]. Upon training the Yolov5 model [6] with 200 epochs, the bounding boxes, object, and class loss in validation data, kept improving until the

3 Link to CW4N: http://www.roboticbuilding.eu/project/wood-reuse/

4 Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D application.

5 Online community platform that allows users to collaborate, publish datasets and use GPU-integrated notebooks.

6 Yolov5 is a compound-scaled object detection model.

200 epochs, which the dataset was trained on. While this ML-supported approach improved material- and process-efficiency, the CE approach remained incomplete. To complete the cycle, the sawdust generated during the milling and cutting phase was reused in another case study involving the robotic 3D printing of a small-scale urban intervention.

4 Additive D2RP

The wood-based polymer structure (Oskam et al., 2022) serving local biotopes was developed in collaboration with Landscape Architecture (LA) at TU Delft and industrial partners. As minimal intervention that stimulates both biodiversity and social accessibility of residual spaces, the intervention takes shape as a 0.8-meter diameter 'planetoid' prototyped using additive D2RP techniques [7]. Its cavernous design facilitates its appropriation by plants, insects, and small animals (Fig. 3).

While the overall form, porosity, and surface tectonics are informed by the use, structural requirements, and environmental conditions of the 'planetoid', the Voronoi mesh itself is optimised for support-free 3D-printing with a biopolymer consisting of cellulose, hemicelluloses, and lignin, which is processed from sawdust that is mixed with a binder, in this case, a thermoplastic elastomer (TPE) that is recyclable.

Support-free 3D printing is achieved by controlling the angles of the Voronoi cells to be within the printing constraints that take into consideration the maximum achievable printing angle, which depends on the viscosity of the material at extrusion temperature as well as cooling i.e., crystallization speed. The printing angles are limited to 45-55 degrees in relation to the printing bed. Since the Voronoi-based cellular structure is an inherently stable self-supporting type of geometry, the cells can be printed at more extreme angles, while continuous toolpaths ensure that the printing process is efficient. The prototype was subdivided into multiple components, allowing the 'planetoid' to be printed in smaller parts. Based on this strategy larger objects are assembled from multiple components (Fig. 3). The size of the assembled object is thus not limited to the size of the 3D printing system. Also, easy transportation and assembly are accounted for.

FIGURE 3 Wood-based polymer 3D-printed 'planetoid'.

7 Link to BcP Planetoid: http://www.roboticbuilding.eu/project/d2rp-for-product-from-landscape-microruin-lab/

5 Discussion

The reclaimed wood studies involved both, subtractive and additive D2RP processes that complement each other with the sawdust generated through milling being reused in 3D printing thus establishing a complete CE cycle. They are proof of concept for novel strategies and approaches that contribute to CO2 reduction since all materials used were recycled and recyclable. The studies involved optimization routines that ensured reduction of material use as well as production time. Hence, overall efficiency increased, which contributed towards achieving a more sustainable building construction approach.

While the processing of reclaimed materials into new, engineered products using advanced robotic and ML-supported techniques as presented in this paper is today achievable, robotization at large introduces challenges in architecture and building construction in terms of infrastructure and skill shift. However, the gain in terms of process, material, and energy- efficiency and implicit CO2 reduction is indisputable. By reusing materials that might otherwise be discarded and by sourcing them locally from deconstructed buildings the carbon footprint associated with the use of new resources and transportation is minimized.

The sustainable opportunities that involve AI-supported D2RP methods relying on CE considerations are various ranging from material to building scale. Hence, further exploration in and advancement of architectural applications is necessary in order to progress towards a society that meets its needs without compromising the ability of future generations to meet their own needs (United Nations General Assembly, 1987).

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References

Ashby, M. F. (2024). *Materials and sustainable development* (Second edition). Butterworth-Heinemann.

Bier, H. (2018). Robotic Building as Integration of Design-to-Robotic-Production and -Operation. In *Robotic building* (S. 97–120). Springer.

Bier, H., Hidding, A., & Galli, M. (2020, Oktober 14). *Design-to-Robotic-Production and -Assembly for Architectural Hybrid Structures*. 37th International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan. https://doi.org/10.22260/ISARC2020/0207

Bier, H., Khademi, S., Van Engelenburg, C., Prendergast, J. M., & Peternel, L. (2022). Computer Vision and Human–Robot Collaboration Supported Design-to-Robotic-Assembly. *Construction Robotics*, *6*(3–4), 251–257. https://doi.org/10.1007/s41693-022-00084-1

Dokter, G., Thuvander, L., & Rahe, U. (2021). How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy. *Sustainable Production and Consumption*, *26*, 692–708. https://doi.org/10.1016/j.spc.2020.12.032

Oskam, P., Bier, H., & Alavi, H. (2022). Bio-Cyber-Physical 'Planetoids' for Repopulating Residual Spaces. *SPOOL*, *9*(1), 49–55. https://doi.org/10.47982/spool.2022.1.04

Peters, J., Tedrake, R., Roy, N., & Morimoto, J. (2011). Robot Learning. In C. Sammut & G. I. Webb (Hrsg.), *Encyclopedia of Machine Learning* (S. 865–869). Springer US. https://doi.org/10.1007/978-0-387-30164-8_732

United Nations General Assembly. (1987). *Report of the World Commission on Environment and Development: Our Common Future, Annex to document A/42/427 – Development and International Co-operation: Environment*. http://www.un-documents.net/wced-ocf.htm