Developing Sustainable Approaches in Architecture (Preprint)

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Abstract
Compared with other industries, the construction sector accounts for about 40% of material-, energy- and process-related carbon dioxide (CO_2) emissions[1], which can be reduced by introducing data-driven Circular Economy (CE) approaches in architecture and building construction[2]. For instance, Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods developed in the Robotic Building (RB) lab at Technical University (TU) Delft are embedding data-driven systems into building processes and buildings. Their potential for contributing to sustainability through increased material-, process-, and energy-efficiency by integrating CE approaches has been explored in several case studies that are presented in this paper.

Introduction
In the last decade, data-driven, and in particular, robotic applications in architecture and building construction have proven their potential for contributing to sustainability through increased material, process, and energy-efficiency (inter al. Vasey et al. 2016; Mayer et al. 2017; Bier, 2018; Rogeau et al., 2020). When integrated with Circular Economy (CE) approaches additional carbon dioxide (CO_2) reduction is to be expected (inter al. Dokter et al. 2021).

Fig. 1: Upcycled plastics pavilion[3]

[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 (2022): https://link.springer.com/book/10.1007/978-3-319-70866-9 and https://link.springer.com/book/9783031141591
[3] Link to RB wiki: http://100ybp.roboticbuilding.eu/index.php/project10:Main

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 (inter al. Nazari and Bier, 2019) that rely on the reuse of materials while taking life-cycles into account.

Design-to-Robotic-Production

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

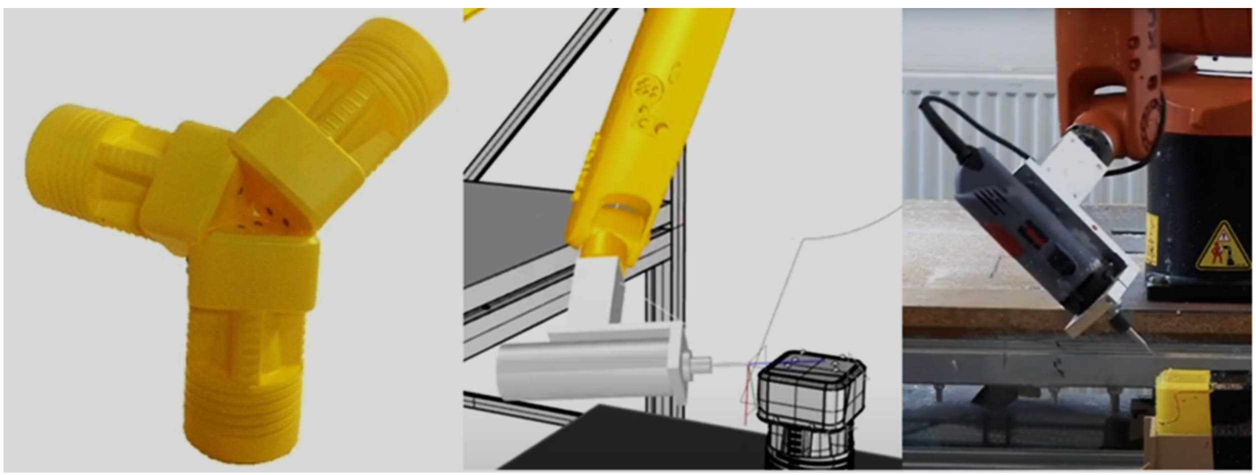

Fig. 2: Node made of three repurposed plastic containers (left) through virtual and physical robotic prototyping (middle and right)

1. Subtractive D2RP

Subtractive D2RP methods were employed in two case studies involving reclaimed plastic and wood. Both aimed to demonstrate the potential of reclaimed materials in architecture (Fig. 1-3). In the case of circular plastic, design possibilities were explored by robotically cutting and reassembling reclaimed containers in order to create nodes for a pavilion (Nazzari and Bier, 2020) that is completely made from reclaimed plastic (Fig. 1). While the design conceptualization started with the reclaimed container and the analysis of its potential, the digital workflow involved data- and performance-driven design, structural and robotic paths optimization. The simulated and the physical prototyping established a feedback loop that facilitated further optimization with respect to tool path and speed in order to improve process and result (Fig. 2).

Similarly, the use of circular wood that has been explored in collaboration with the University of Applied Science (UAS) Amsterdam involves reuse of reclaimed wood by laminating layers of wood into a larger component and milling it (Fig. 3) into curvilinear beams that are connected to topologically optimized 3D-printed metal nodes[4].

ML-supported approaches involving Computer Vision (CV) were integrated with the procurement of wood. CV helped identify defects in the wood with the goal to demarcate and remove the unusable parts that would potentially jeopardize the structural integrity of the to-be-built structure. The defect identification using images of wooden boards is, thus, followed by boundary detection and extraction. Once the CV is able to identify the size of the board, a trained model identifies and demarcates the defects with boundary boxes (Fig. 4). These are then converted to text, i.e., coordinates data that is used within Grasshopper Rhino, to generate a cutting pattern of the usable wood.

Fig. 3: Packed, glued (left) and milled (middle and right) reclaimed wood

Obtained large-scale dataset consists of 4000 wood images with visible defects already 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 200 epochs that the dataset was trained on, while the class loss seemed to be going up beyond 80 epochs and the precision metrics improved up to 120 epochs. The trend on the correlogram showed that defects in general tended to be closer to the central portions of the wooden pieces along the y-axis (Fig. 4).

While this ML-supported approach improves material- and process-efficiency, the CE approach remains incomplete. In order to complete the CE cycle, the sawdust generated during the milling and cutting phase was reused in another case study involving the robotic 3D-printing of

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[4] Link to CW4N: http://www.roboticbuilding.eu/project/wood-reuse/

[5] Link to online community platform for data and machine learning scientists allows users to collaborate with other users, find and publish datasets, and use GPU integrated notebooks.

[6] Yolov5 is a compound-scaled object detection model.

a small-scale urban intervention using wood-based polymer (Oskam et al. 2022). While printing with sawdust has been explored in various projects (inter al. Correa et al. 2015; Kariz et al., 2016) that have proven its potential for non-structural applications, presented case study has optimized structural properties at small urban furniture scale.

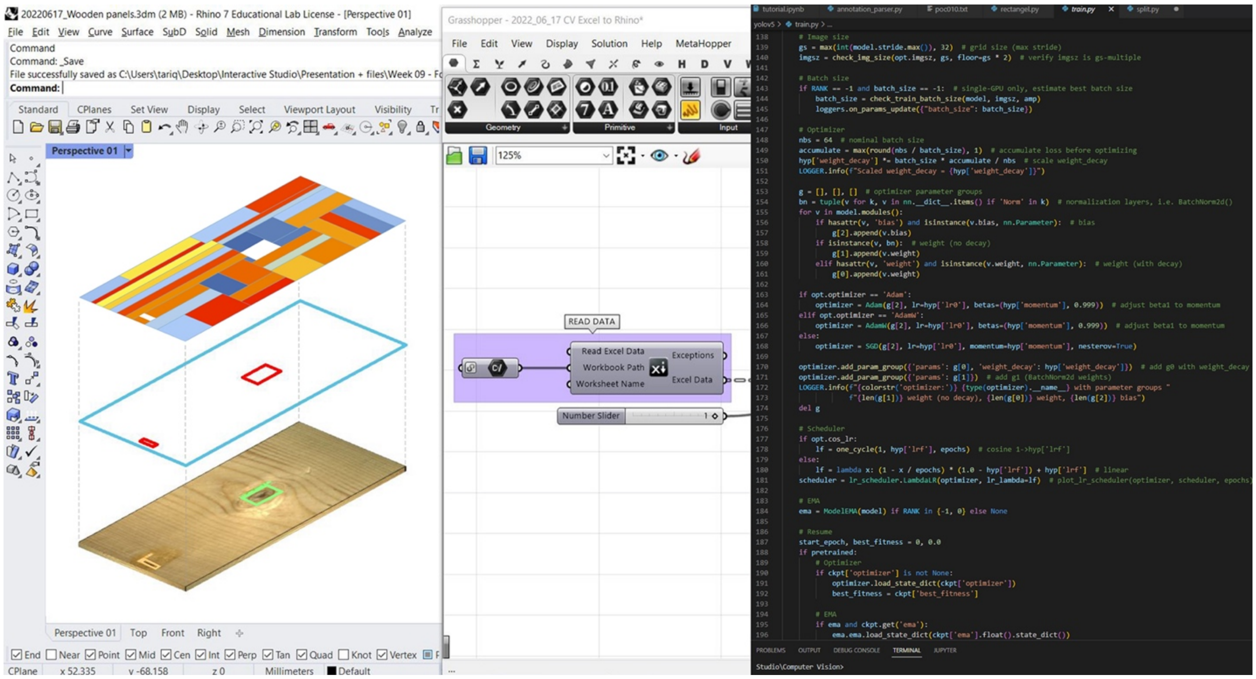

Fig. 4: ML-supported processing of reclaimed wood panels

2. Additive D2RP

The 3D-printed urban intervention developed in collaboration with Landscape Architecture (LA) at TU Delft implements minimum interventions that stimulate both biodiversity and social accessibility of residual spaces (inter al. Oskam et al., 2020). The interventions take shape in form of 0.5-1-meter diameter 'planetoids' prototyped using additive D2RP techniques. Their cavernous design facilitates their colonisation through plants, insects, and small animals.

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). Support-free 3D printing is achieved by controlling the angles of the Voronoi cells to be within the printing limitations. The maximum achievable printing angle 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 cellular structure is an inherently stable self-supporting type of geometry, the cells can be printed at more extreme angles. Continuous toolpaths ensure that the printing process is efficient.

Fig. 5: Wood-based polymer 3D-printed ‘planetoid’

The prototype was subdivided into multiple components, allowing the ‘planetoid’ to be printed in multiple parts. Based on this strategy larger objects are assembled from multiple components. The size of the assembled object is thus not limited to the size of the 3D printing system (Fig. 5). Also, easy transportation and assembly are accounted for.

Discussion

While the reclaimed plastic study involved subtractive D2RP, the reclaimed wood studies involved both, subtractive and additive D2RP, and established a full CE cycle. They all are proof of concept for novel strategies and approaches that contribute to CO2 reduction in particular when considering their life-cycle as all materials used are recyclable. They involve structural, environmental, robotic path and ML-supported material optimization routines that ensure reduction of material use as well as production time. While the overall productivity increases, material use and production time are minimized, which contributes towards achieving a more sustainable building construction approach in particular when integrated with CE considerations.

Robotization integrated with CE considerations introduces challenges in architecture and building construction, the gain in terms of process, material, and energy-efficiency is, though, indisputable. The sustainable opportunities that involve D2RP methods are various and 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 (inter al. UN, 1987).

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