

# The parametric design and robotic assembly of a timber column

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## Abstract

The construction industry nowadays is facing many challenges to reduce its environmental impact and to become more efficient, sustainable and safe. One way to help tackle these challenges is to use more automation. This thesis focuses specifically on timber construction. The goal of this project is to design, engineer and robotically assemble a parametric timber structure. This goal can be subdivided in two parts: the parametric design and the robotic assembly.

First of all, a design concept is made. The structure is a column that consists of beams stacked two by two on top of each other. By changing the angle at which these beams are stacked, the column form can be changed. Subsequently, an optimization is done on a asymmetric pavilion structure with three of these columns. The column forms in the pavilion are optimized by minimizing the most critical force: tension in the joints. The optimization process reduces the tension by approximately 43%, by balancing wind surface area in every direction and by dividing tension more equally over the joints. The optimization results in a pavilion structure with organic columns that meet the structural requirements, in contrary to a non-optimized structure with straight columns that uses the same amount of material.

Then, the robotic assembly process is worked out to build the optimized timber column. The robotic set up consists of two robots that work together. One robot picks and places timber beams in the correct position with a pneumatic gripper. The other robot connects the timber beams with screws. To do this, a robotic screwing end effector is developed with a pneumatic screw machine, a magnetic screw holder and a capacitive proximity sensor. The robots can work safely together by using multi move, careful path planning and collision checks. The full assembly process is tested and fine tuned and the optimized column is constructed.

The end result of the project is a full size, robotically constructed, structurally optimized, parametric timber column. Furthermore, a robotic set up is developed where it is possible to automatically assemble a timber structure with screws.

*Keywords: parametric design, optimization, structural engineering, robotic assembly, timber construction, automation, screwing, end effector*

## 1 Introduction

The building sector faces large challenges in the upcoming years on sustainability, safety and productivity. These challenges ask for rethinking current construction processes and a more sustainable material use. Automation could help with these challenges, because it can lead to higher productivity, improved quality, increased sustainability, mass customization, improved safety and dealing with skilled labor shortage. This project will focus on the automation of assembling a timber structure.

Automation of construction of timber structures is not entirely new. An example is the DFAB house [1], where robots cut and drill timber beams and move it towards the right location, where it is then manually screwed together. Another example is the re-configurable structure from University of Southern Denmark [2], where two collaborative robots screw a timber structure together and use a wrist camera to detect the screw holes. However, what can be seen in the research in the automation of robotic timber construction, is that fully automated construction processes are rare. In most cases manual steps are required or human intervention is necessary to correct for failures.

The goal of the graduation project is to: Design, engineer and robotically assemble a parametric timber structure. This main goal can be subdivided in two sub-goals: 'Design a parametric timber structure' and 'Robotically assemble the timber structure', covered in section 2 and 3 respectively. The final result is covered in section 4.

## 2 Design

In this section the design, calculation, optimization and result of the parametric timber structure are covered.

### 2.1 Global design

As a global design a column structure is chosen where equally sized timber beams are stacked two by two on top of each other and connected with a vertical screw. By rotating the beams and stacking them in a different angle, various column forms can be created. The column will be part of a nature-inspired pavilion structure, where multiple columns are placed underneath one Cross Laminated Timber (CLT) roof. The design concept is shown in Figure 1.

The form of the column will be parametrically optimized, so that the strongest and therefore the most material efficient column combination is found. In the variation of the column form, the length of the beams always remains constant.

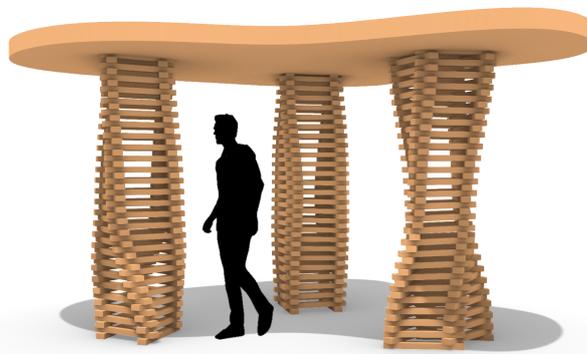


Figure 1: Global design

### 2.2 Calculation

The structural scheme as used for the calculations can be seen in Figure 2. The timber beams are represented by their center lines, to which the cross section of the beam and an orthotropic material (C24 timber) are assigned. The direction of the timber fiber is parallel to the direction of the center line. The connections between the beams are represented by a "connection line". This line vertically connects the intersection points of two beam center lines on top of each other. The connection lines are fixed to the beam center lines, only in the middle of the line the rotation around the vertical ( $z$ ) axis is free. This represents a joint with one screw, which can rotate around the axis of the screw. The same material properties are used, only this time the direction of the fiber is perpendicular to the direction of the element. Also, the connection lines have no mass, as this mass is already included in the beam center lines. The top and bottom of the column are fixed to the roof and ground.

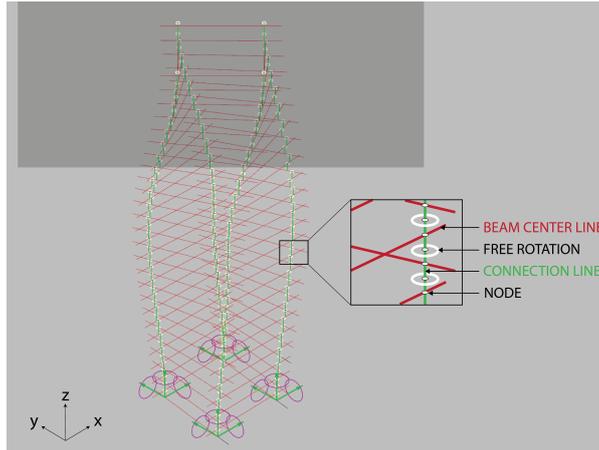


Figure 2: Structural scheme of one column

The different types of loads applied to the structure are: gravity, imposed load, snow load and wind load. The design is a roof structure which is not accessible other than for maintenance and the roof angle is  $0^\circ$ . Therefore, the imposed loads on the roof are a distributed load ( $q$ ) of  $1.0 \text{ kN/m}^2$  and a point load ( $Q$ ) of  $1.5 \text{ kN}$ . The snow load ( $s$ ) on the roof of the structure is calculated as  $0.56 \text{ kN/m}^2$ , applied equally on the full roof area. The structure can be located in an open area in the region of Eindhoven, the Netherlands, so the extreme wind pressure ( $q_p$ ) is  $0.49 \text{ kN/m}^2$  over the full height of the structure. The total wind load consists of horizontal wind pressure and suction on the column and roof edges, vertical wind pressure and suction on the roof and wind friction. The roof can be categorized as an empty, free standing canopy. Therefore, the roof is subdivided in different areas that have different pressure coefficients, which are approximated by looking at the local tangent of the roof edge. The wind load is applied and checked in eight wind directions, namely:  $x$ ,  $xy$ ,  $y$ ,  $-xy$ ,  $-x$ ,  $-x - y$ ,  $-y$  and  $x - y$ .

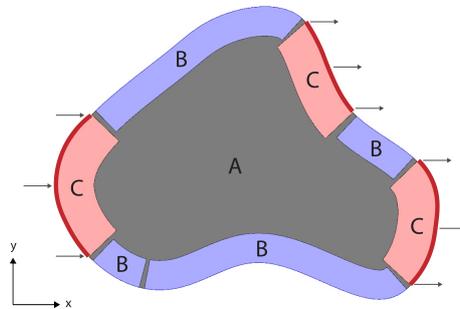


Figure 3: Wind load roof approximation ( $x$  direction)

### 2.3 Detailing

The screw joint is calculated for tension and shear. In tension, the screw is checked for the pull-out strength of the threaded part, the pull-through strength of the screw head and the tension strength of the screw. The lowest and thus governing tensile strength is the value of the pull-through strength of the screw head, which is  $1.63 \text{ kN}$ . The shear capacity of the screw is calculated for all possible failure modes and the lowest and thus governing value is  $1.94 \text{ kN}$ . The screw locations must meet the Eurocode standards of the minimum distance between screws and the minimum distance to the timber edges and ends. To make sure the minimum distances are met, each screw is shifted half the minimum screw distance ( $a_2$ ) from the middle line of the timber beam. Therefore every screw has at least  $a_2$  distance between neighbouring screws. This concept is illustrated in Figure 4. The beam width and extension are chosen so that also the end and edge distances are met.

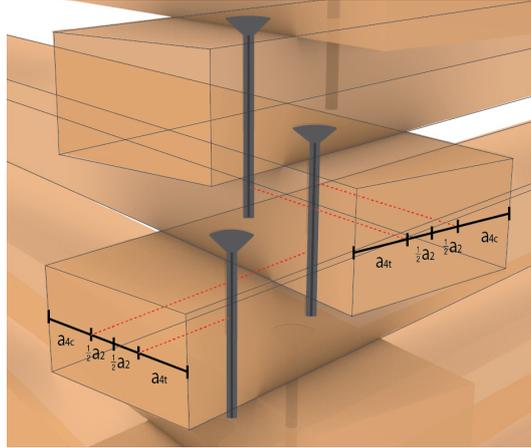


Figure 4: Screw locations

## 2.4 Optimization

What can be seen when the pavilion structure is calculated, is that the most critical force in the structure is the tension force in the screw joint. Therefore, the goal of the optimization process is to limit this tension force, so that minimal material has to be used. The optimization is done in the Grasshopper plugin Octopus.

The variables of the optimization can be seen in Figure 5. At the top, middle and bottom of the column two variables can be varied: rotation ( $R$ ) and diameter in one direction ( $D$ ), which leads to six variables per column. In the pavilion, each column generates its uniquely optimized form. The optimized result is compared to a structure with straight columns positioned in two different ways:  $0^\circ$  and  $45^\circ$  rotated (see Figure 6).

The tension forces are highest during the Ultimate Limit State load combination with wind load including wind suction on the roof. Therefore, this load combination is used for optimization. The wind is individually applied in all eight wind directions.

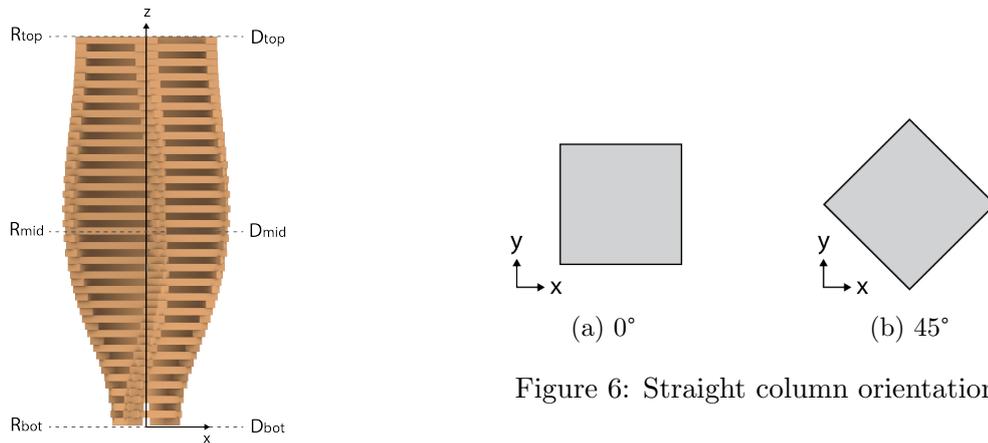


Figure 5: Optimization variables

The result of the asymmetric optimization can be seen in Figure 7. The wind area of the three asymmetric columns together is calculated for every wind direction, which can be seen in Figure 1. As can be seen is that the maximum wind area (highlighted in red) is less in the optimized structure, than for the structure with straight columns. The wind area of the optimized structure is divided more equally over all wind directions and thus has a lower peak value.

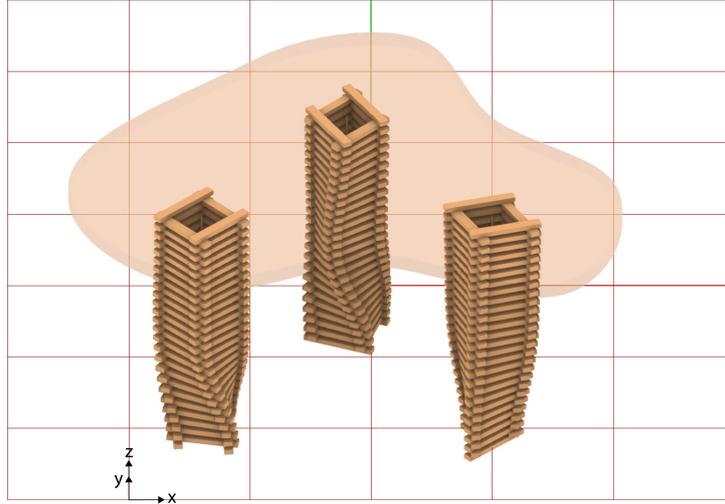


Figure 7: Final result optimization asymmetric pavilion

Table 1: Comparison wind surface area columns asymmetric structure

	Wind surface area [ $m^2$ ]				
	x	xy	y	-xy	Total
0	4.12	5.71	3.96	5.71	19.50
45	5.71	3.96	5.71	4.12	19.50
Optimized	5.60	4.78	5.17	4.99	20.53

The reaction forces in the asymmetric structure per column (C1, C2 & C3) are given in Table 2. It can be seen that the total horizontal reaction force (highlighted in blue) is lower when the wind surface area is lower. So, the maximum wind load in the most critical wind direction is lower for the optimized structure than for the straight structures. Furthermore, the maximum tension force (highlighted in red) is lower when it is divided over more column corners. In the straight column structures, all column corners are oriented in the same direction. Therefore, there are critical wind directions where the tension is only divided over one corner per column, which leads to a peak tension value. In the optimized structure, this tension is more equally divided in every wind direction, so the maximum value is lower. This phenomenon is visualized in Figure 8.

Table 2: Reaction forces asymmetric structure (Load combination: gravity + wind x)

		Reaction force [kN]												
		1			2			3			4			Total
		x	y	z	x	y	z	x	y	z	x	y	z	x
0	C1	-0.23	0.01	0.85	-0.23	0.01	0.83	-0.23	0.00	-0.70	-0.23	0.00	-0.71	-0.92
	C2	-0.23	-0.01	0.70	-0.23	-0.01	0.71	-0.23	-0.01	-0.85	-0.23	-0.01	-0.83	-0.93
	C3	-0.22	0.00	0.75	-0.22	0.00	0.73	-0.22	0.00	-0.75	-0.22	0.00	-0.74	-0.87
	Total													-2.72
45	C1	-0.32	0.01	0.12	-0.32	0.01	1.59	-0.32	0.01	-1.41	-0.32	0.01	0.05	-1.28
	C2	-0.32	-0.01	-0.08	-0.32	-0.01	1.40	-0.32	-0.01	-1.59	-0.32	-0.01	-0.09	-1.28
	C3	-0.30	0.00	0.02	-0.30	0.00	1.44	-0.30	0.00	-1.44	-0.30	0.00	-0.02	-1.21
	Total													-3.78
Opt	C1	-0.31	0.00	0.53	-0.28	-0.01	-1.15	-0.25	0.00	1.37	-0.28	0.00	-0.34	-1.13
	C2	-0.33	0.00	0.83	-0.31	0.01	1.02	-0.28	-0.01	-1.24	-0.37	-0.02	-1.02	-1.29
	C3	-0.30	-0.02	-1.30	-0.33	0.02	0.70	-0.35	0.01	-0.70	-0.31	0.01	1.30	-1.29
	Total													-3.70

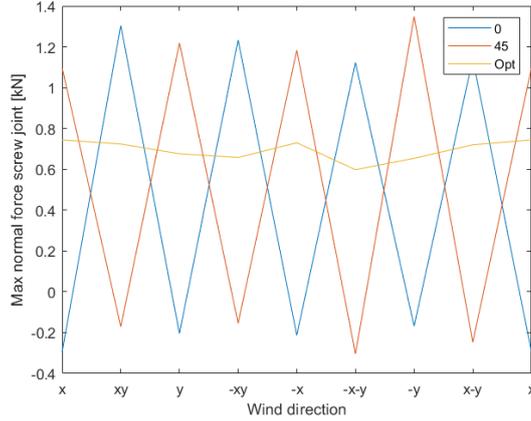


Figure 8: Maximum normal force in screw connection per wind direction

## 2.5 Result

The comparison between the optimized structure and the structure with straight columns can be seen in Table 3. As can be seen, the maximum tension force in the screw connections of the optimized structure is reduced with almost 43% compared to the straight column 0°. The maximum Unity Check of the optimized structure is reduced by almost 5%. This reduction is a bit less extreme than the reduction in tension force. That is due to the fact that the shear force in the optimized structure slightly increases, which causes an increase in the most governing Unity Check (tension and shear in the screw). However, it can be concluded that the optimized structure is the only structure that suffices the structural criteria, while in all three structures exactly the same amount of material is used. Therefore, the optimization proves to be successful.

Table 3: Comparison before and after optimization

	Max $N_t$ [kN]	Difference [%]	Max UC	Difference [%]
<b>0</b>	1.30	0.00	1.05	0.00
<b>45</b>	1.35	3.37	1.09	3.81
<b>Optimized</b>	0.74	-42.94	1.00	-4.76

## 3 Assembly

This section covers the robotic assembly of the parametric timber structure, which is done with screws.

### 3.1 Set-up

The robotic construction is done with two robots: the ABB IRB1600 (Robot 1), which handles the screwing and the ABB IRB1200 (Robot 2), which handles the timber beams.

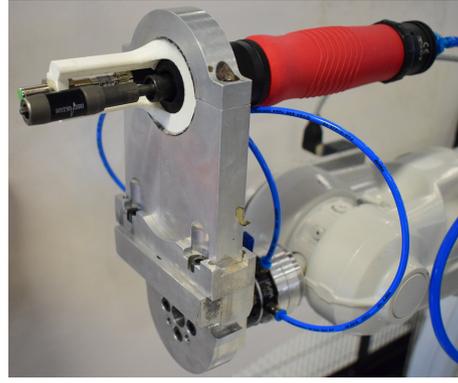
Picking and placing of the timber beams is done with a gripper end effector, which can be seen in Figure 9a.

Picking and placing a screw by a magnetic screw holder with ring magnet, especially made for long and heavy screws: the WERA Impaktor. For screwing a screw machine is used and the screw machine that fitted all requirements best is the RODAC RC3460. To ensure that the screws will still always be screwed in at the right depth, a capacitive proximity sensor is added: the Autosen AC006.

The screwing machine is connected to the robot with a stiff aluminium holder. The sensor is attached to the screwing end effector with a 3D printed bracket inside the holder, which enables the sensor to be close to the bit head. The full screwing end effector can be seen in Figure 9b.



(a) Gripper

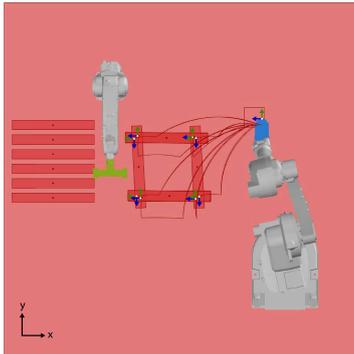


(b) Screw machine

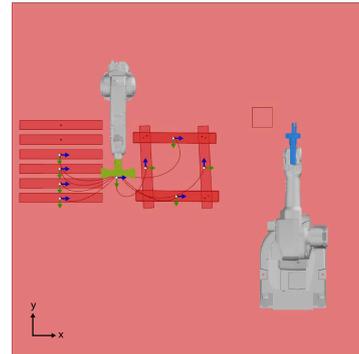
Figure 9: Robotic end effectors

### 3.2 Path planning

The positioning of the robots is carefully determined. The robots are each placed in one corner of the table, so they both approach the column structure from different directions, which minimizes the chance for collisions. Furthermore, it gives them the most possible space to move in, which limits the chance for unexpected movements or movements through singularity points. Both robots use fly by points, so they move around each other and the column structure. The paths are visualized in Figure 10.



(a) Robot 1



(b) Robot 2

Figure 10: Path planning

The paths consist of joint movements and linear movements. The large movements between picking up and placing are done with joint movements with a relatively high velocity. When the robot is near the beam, it makes a linear movement downwards with a lower (thus more precise) velocity. The fly by points in between joint movements have a zone, which indicates that the robot does not have to pass the point exactly, but can approach it within the assigned zone, which leads to smoother and faster paths.

#### 3.2.1 Screwing

Picking up the screw is done by moving the magnetic screw holder towards the screw. To make sure the bit always clicks correctly into the screw head, the robot rotates around the  $z$ -axis above the screw. Subsequently, the robot moves towards the screw position and the screwing procedure starts. The robot moves vertically downwards with a speed ( $v_{down}$ ) calculated according to Equation 1. The downward speed is an approximation, because the screw machine does not always rotate with exactly the same value, due to variations in the required torque in the timber. The spring inside the screwing machine accounts for these inaccuracies. The linear screwing

movement stops when the sensor gives a signal that the screw is deep enough inside the timber beam. The sensor is connected to the I/O ports of the robot, so when the sensor detects the timber beam, the sensor signal changes and the robot stops with the downward movement.

$$v_{down} = \frac{RPM}{60} Lead \quad (1)$$

In which:

$RPM$  = rotations per minute screw machine = 550  $RPM$

$Lead$  = screw lead = 0.90  $mm$

### 3.2.2 Multi move

During construction it is necessary that the two robotic arms work together and wait for each other to perform certain tasks. To do this, two "Wait Sync Task" synchronization points are defined in the robot code. The robots can only continue with their next task once both robots have reached the specific synchronization point.

First of all, Robot 1 can pick up a screw and Robot 2 can pick up a beam simultaneously. Then, Robot 2 can place the beam at the programmed position in the column. Once the beam is in the correct position, Robot 1 can move the picked up screw towards the correct screw position and screw in the screw. Then, Robot 1 can pick up the second screw and screw this in at the other side of the timber beam. Once both screws are in, Robot 2 can let go of the beam and proceed with picking up and placing the next beam. This procedure (visualized in Figure 11) is repeated until the full column part is constructed.

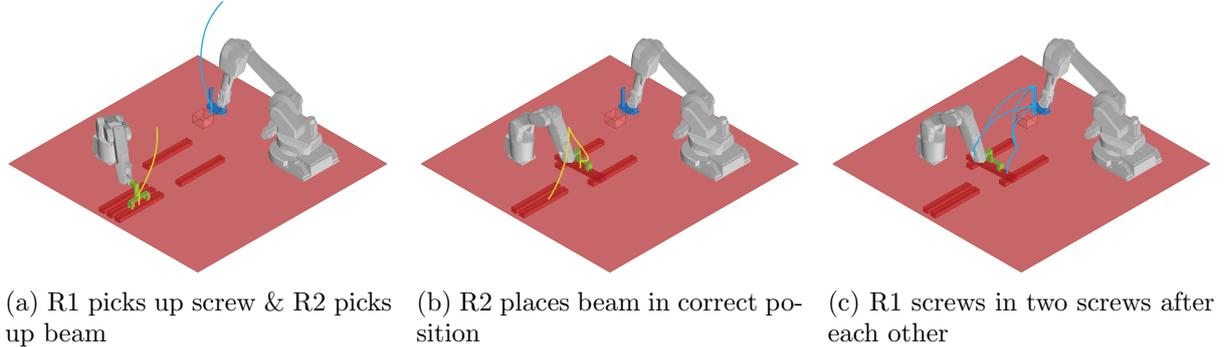


Figure 11: Construction procedure

### 3.2.3 Collision check

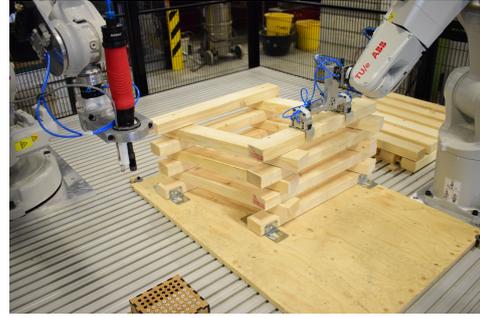
A collision check is done for the full building sequence to make sure that the robots, end effectors and building materials do not crash in to each other. The following geometries are modeled and imported into RobotStudio: Robot 1, Robot 2, Gripper tool, Screwing tool, Beam, Screw and Ground table. Then, collision sets are defined, which can detect whether a geometry (nearly) collides with another geometry. A near miss criterion is added, so the geometries cannot be closer than the assigned near miss value to each other. The full assembly procedure is simulated including collision check before construction.

### 3.2.4 Construction

Because the arm reach of the robots is limited, a structure height of approximately 0.6  $m$  can be achieved. Therefore, the full column is constructed in four parts of approximately thirteen layers each. During the construction of the first two beams, no screws are screwed in. These beams are placed by the gripper and then manually fixed to a timber ground plate using corner brackets, which can be seen in Figure 12a. The rest of the layers are fully robotically constructed as in Figure 12b.



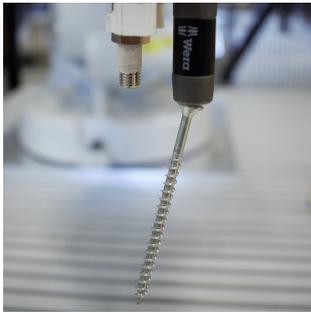
(a) First two beams



(b) Rest of beams

Figure 12: Column construction

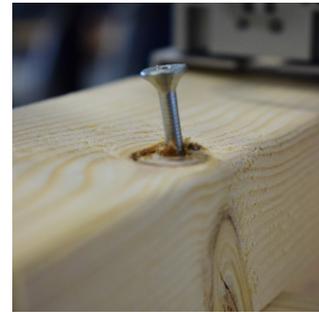
Every now and then a human intervention was needed. In total six construction errors were found, which can be seen in Figure 13. The amount of times an error occurred for each column part can be seen in Table 4. In total 188 screws and 102 beams are placed. The success rate of the different construction steps can be found in Table 5. A video is made of the robotic construction process [3].



(a) Screw not picked up correctly



(b) Screw not in deep enough



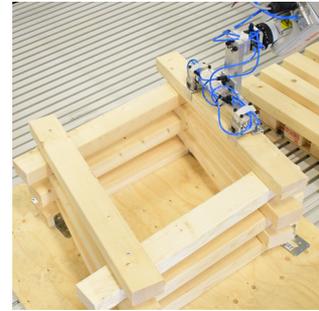
(c) Screw skewed



(d) Timber split



(e) Space between beams



(f) Structure too high

Figure 13: Construction errors which required human intervention

Table 4: Number of errors per column part

Error	Part 1	Part 2	Part 3	Part 4
a	0	0	1	0
b	3	0	0	0
c	1	1	0	0
d	0	0	1	0
e	2	3	1	2
f	6	1	0	0
<b>Total</b>	<b>12</b>	<b>5</b>	<b>3</b>	<b>2</b>

Table 5: Success rate per construction step

Step	Success rate [%]
Pick up screw	99.5
Place screw	100.0
Screw	96.8
Pick up beam	100.0
Place beam	85.3
<b>Total</b>	<b>96.3</b>

## 4 Result

The column that is chosen to be constructed is one of the optimized columns from the asymmetric structure, which can be seen in Figure 14a. The robotically constructed timber column can be seen in Figure 14b.

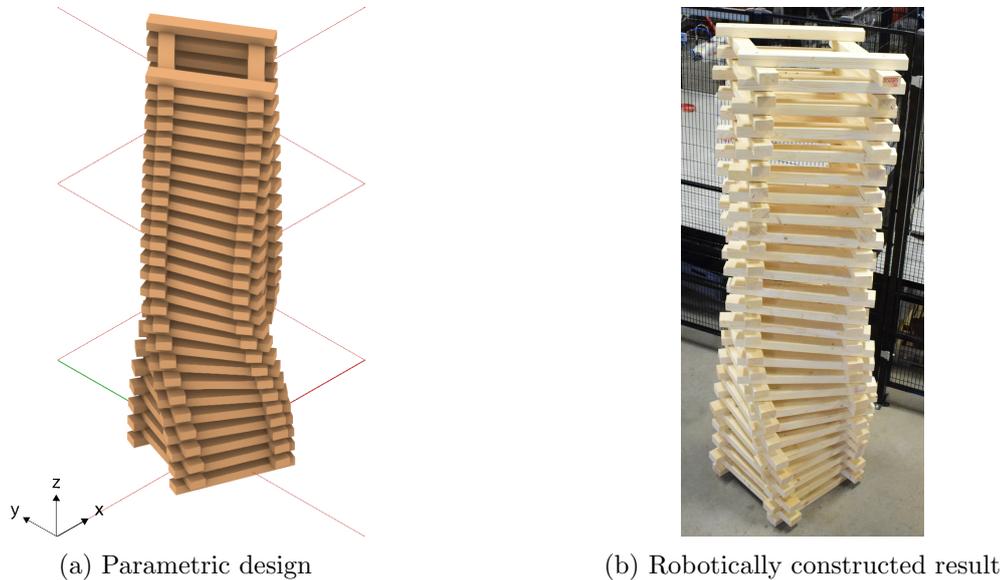


Figure 14: Comparison design versus robotic construction

## 5 Conclusion

All in all, the objective to design, engineer and robotically assemble a parametric timber structure is achieved. A parametric column structure is optimized and structurally improved compared to a simple, straight column. This column is robotically constructed with two robot arms, one with a gripper end effector and one with a screwing end effector. The success rate of all robotic construction steps is currently 96.3%, but has the potential to increase even further.

## References

- [1] K. Graser, M. Baur, A. Apolinarska, K. Dörfler, N. Hack, A. Jipa, E. Lloret, T. Sandy, D. Pont, D. Hall, and M. Kohler, “DFAB HOUSE - A Comprehensive Demonstrator of Digital Fabrication in Architecture,” in *Fabr. 2020 Mak. Resilient Archit.*, 4 2020, pp. 130–139.
- [2] A. Kunic, A. Kramberger, and R. Naboni, “Cyber-Physical Robotic Process for Re-Configurable Wood Architecture Closing the circular loop in wood architecture,” *Digital fabrication and robotics*, vol. 2, 9 2021.
- [3] L. Vrenken, “Robotic Assembly of a Parametric Timber Column,” 3 2023. [Online]. Available: <https://www.youtube.com/watch?v=ZgWgojllBio>