(re)assembly

towards a future of automatic reuse and reconfiguration

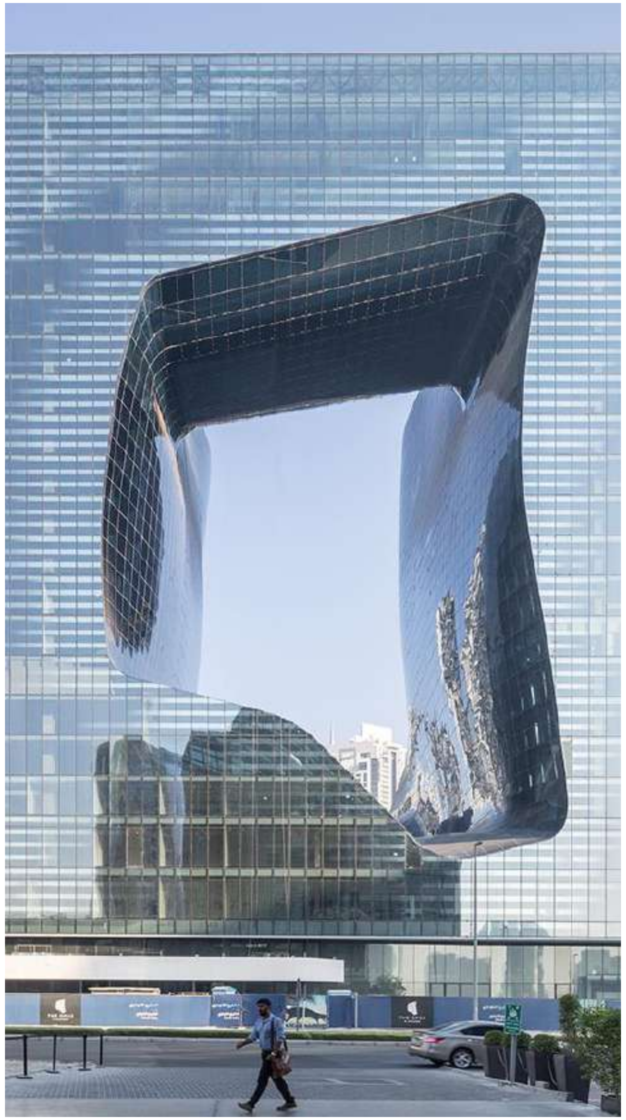
TU Delft

Jirri van den Bos

1 Introduction

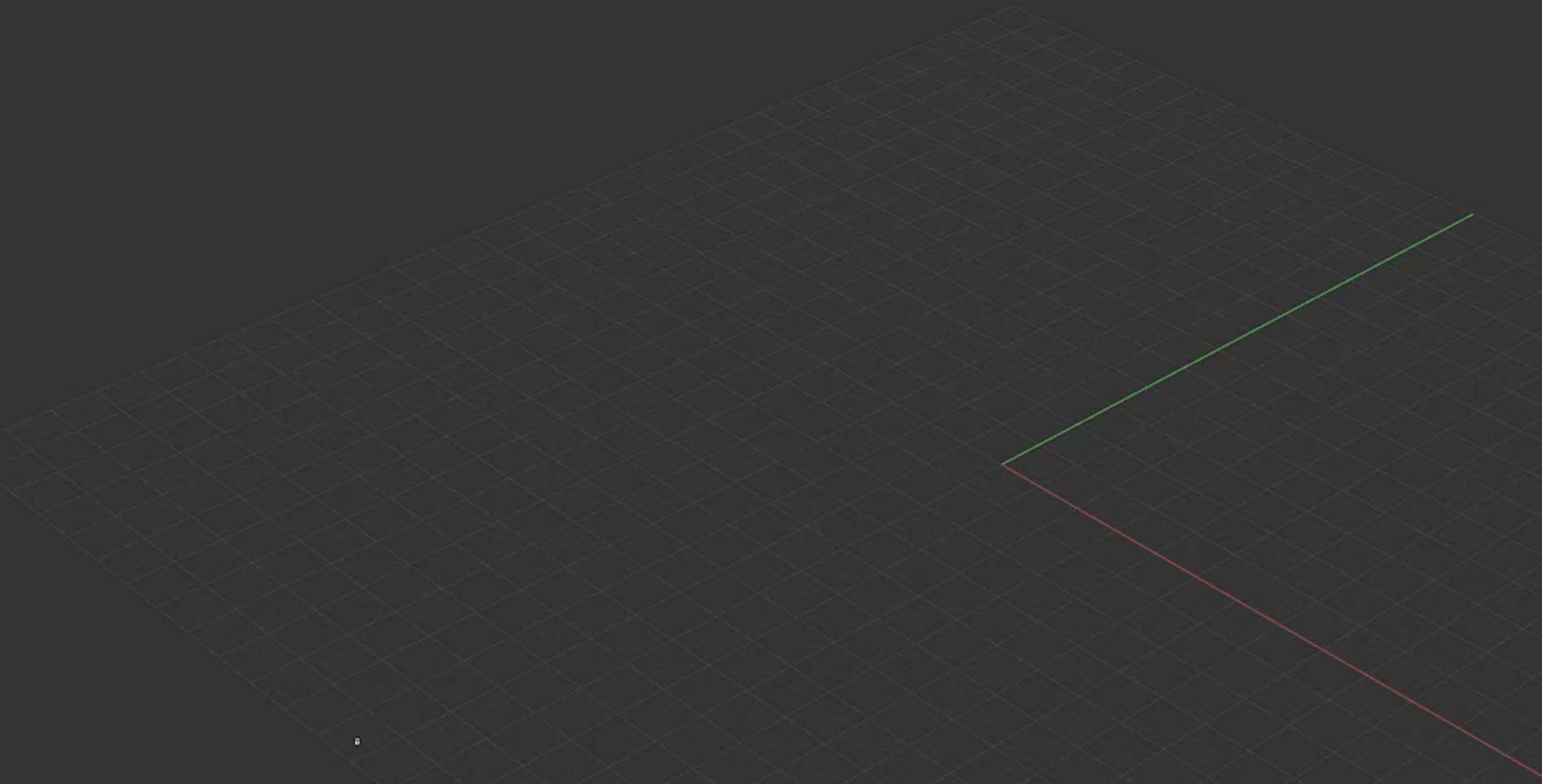
low productivity & high emissions

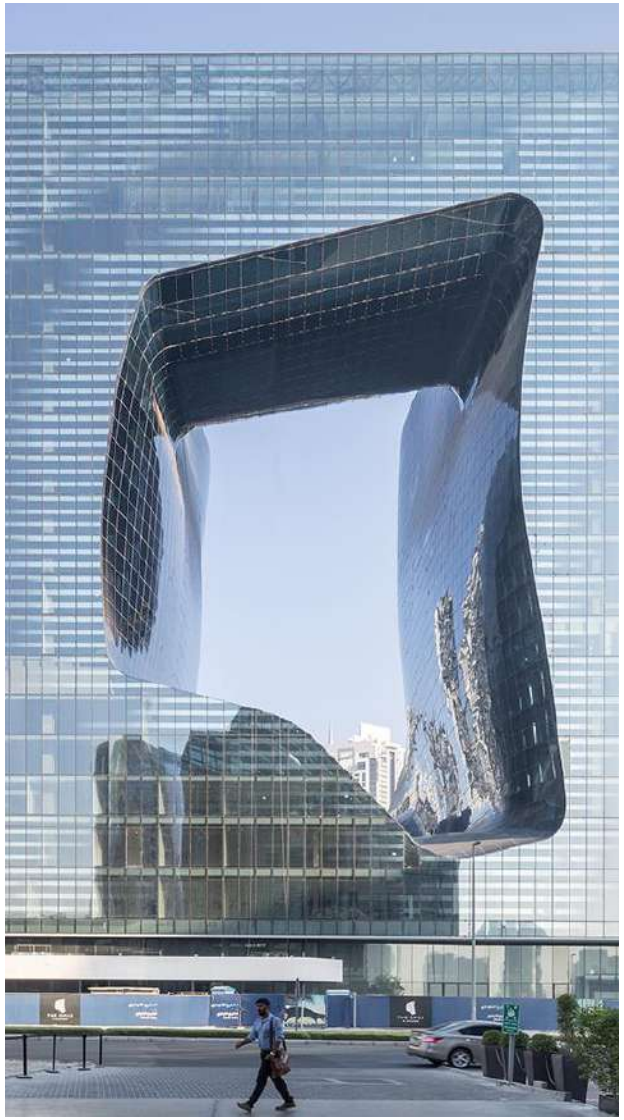
digital revolution



The Opus- Zaha Hadid Architects

Emporia - Wingardh Arkitekt Kontor AB – Folcra



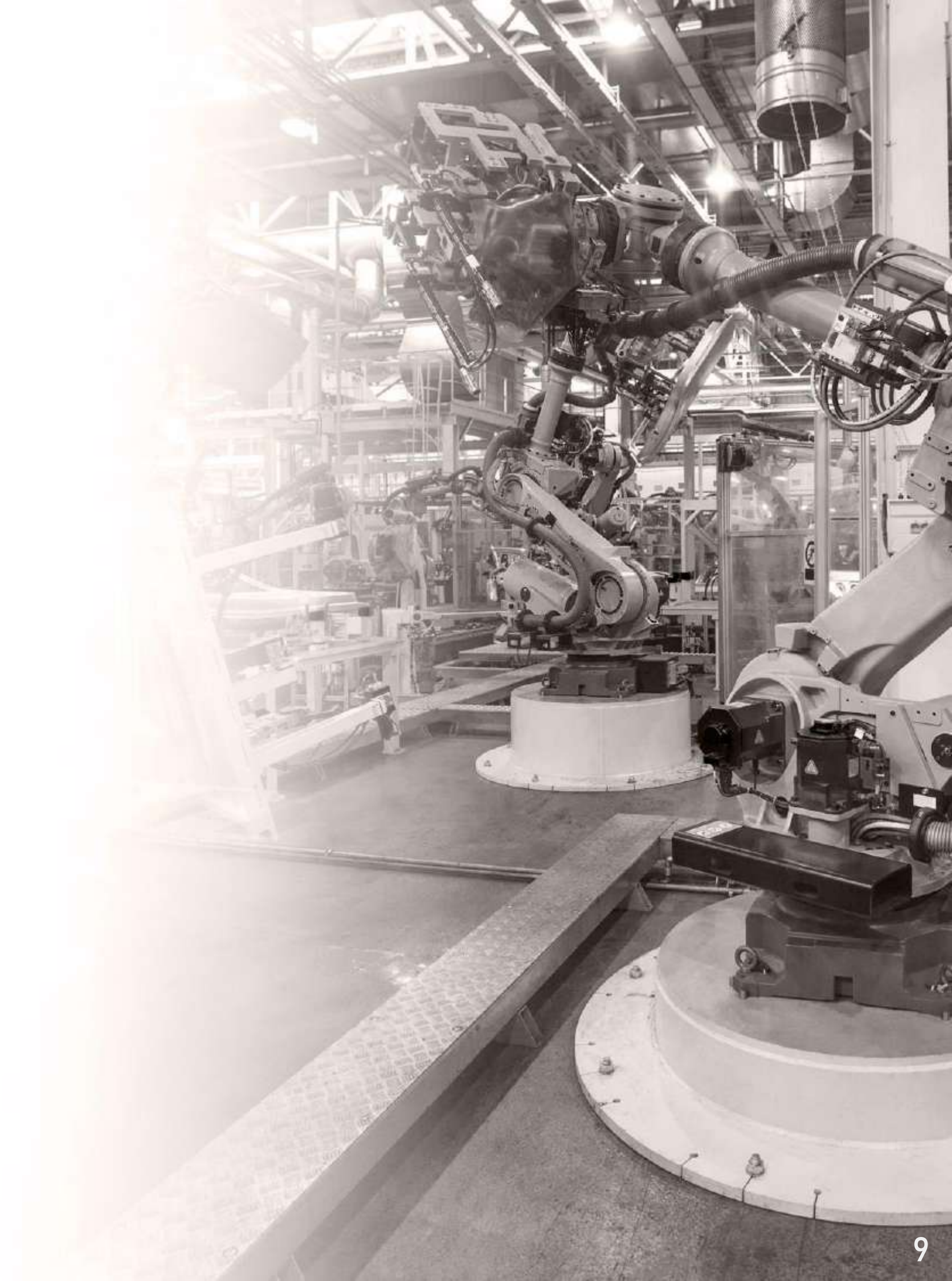


The Opus- Zaha Hadid Architects

Emporia - Wingardh Arkitekt Kontor AB – Folcra

With growth of curved shapes predicted we have a unique opportunity to pre-emptively tackle productivity and emission issues by enabling the reuse of nodes & beams

2 Methodology



Problem statement

Realising freeform building geometry requires complex and time-consuming processes in computational shape rationalization, fabrication of custom nodes & beams and in-situ construction. Custom building elements are not suitable for reuse and are likely to be recycled in a relatively high energy-consuming melting process.

Research question

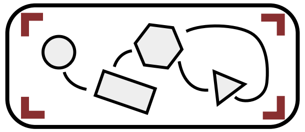
How can a design to production workflow be developed towards automatic assembly and circularity of nodes & beams in different freeform building facades?

Framework

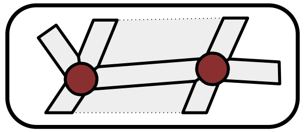
1 mesh rationalisation

$$k := \langle N, \frac{d}{ds} T \rangle$$

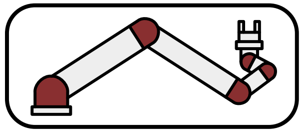
2 design boundaries



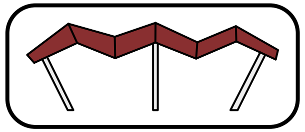
3 node design

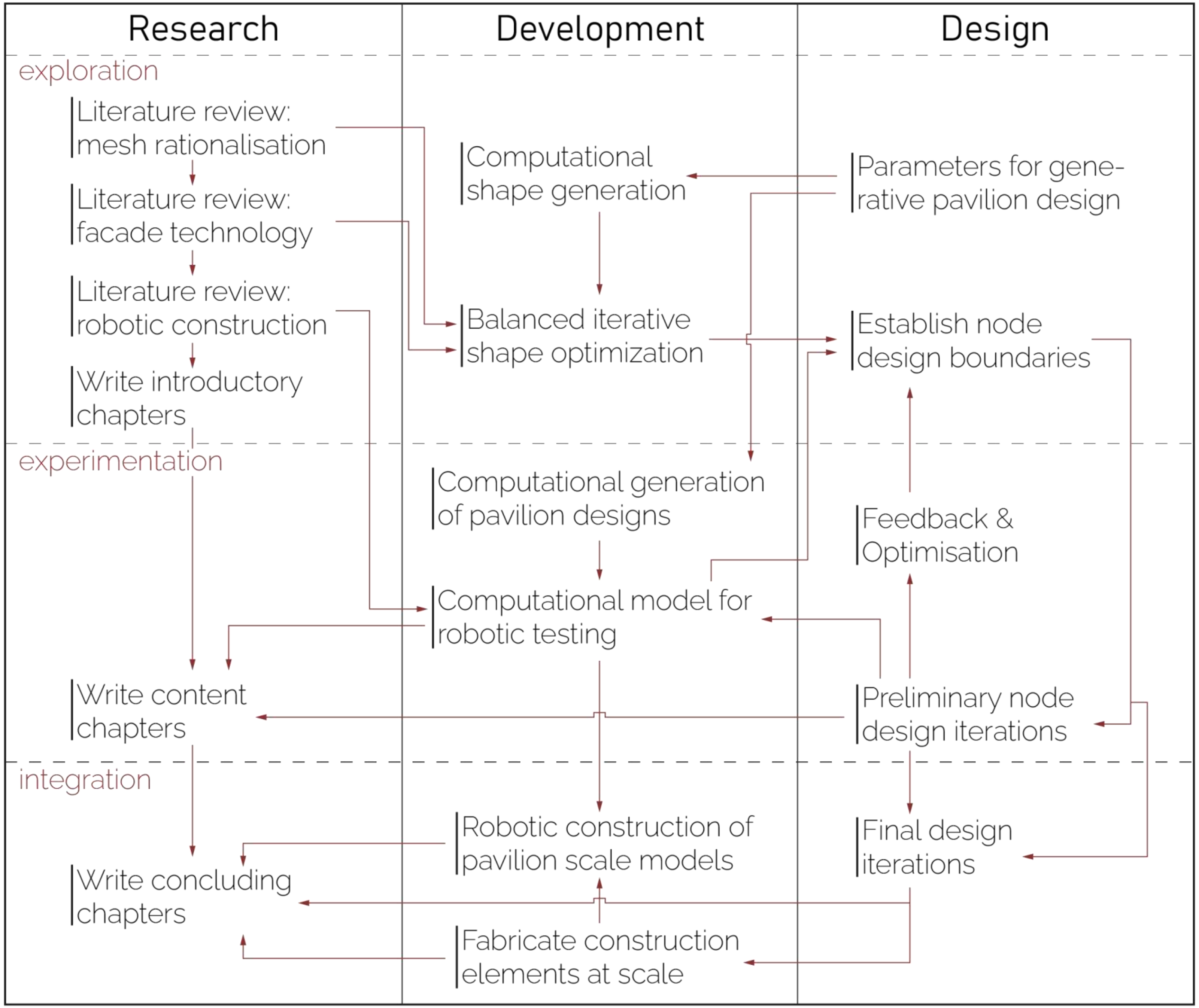


4 robotic assembly



5 pavilion construction

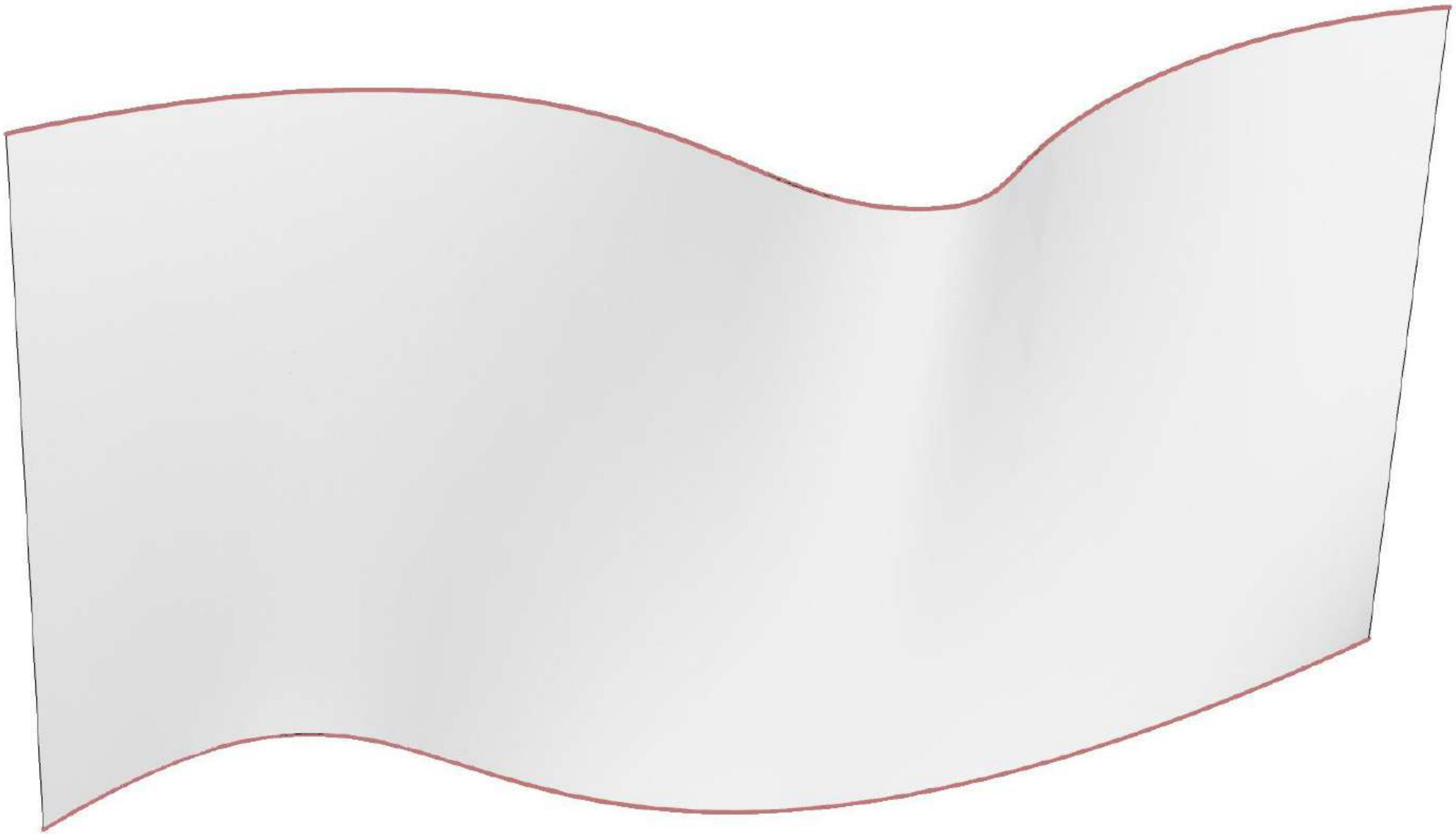


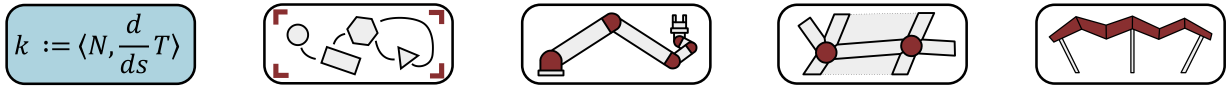


3 Mesh Rationalization

How can optimal rationalizations of freeform building facades be determined?

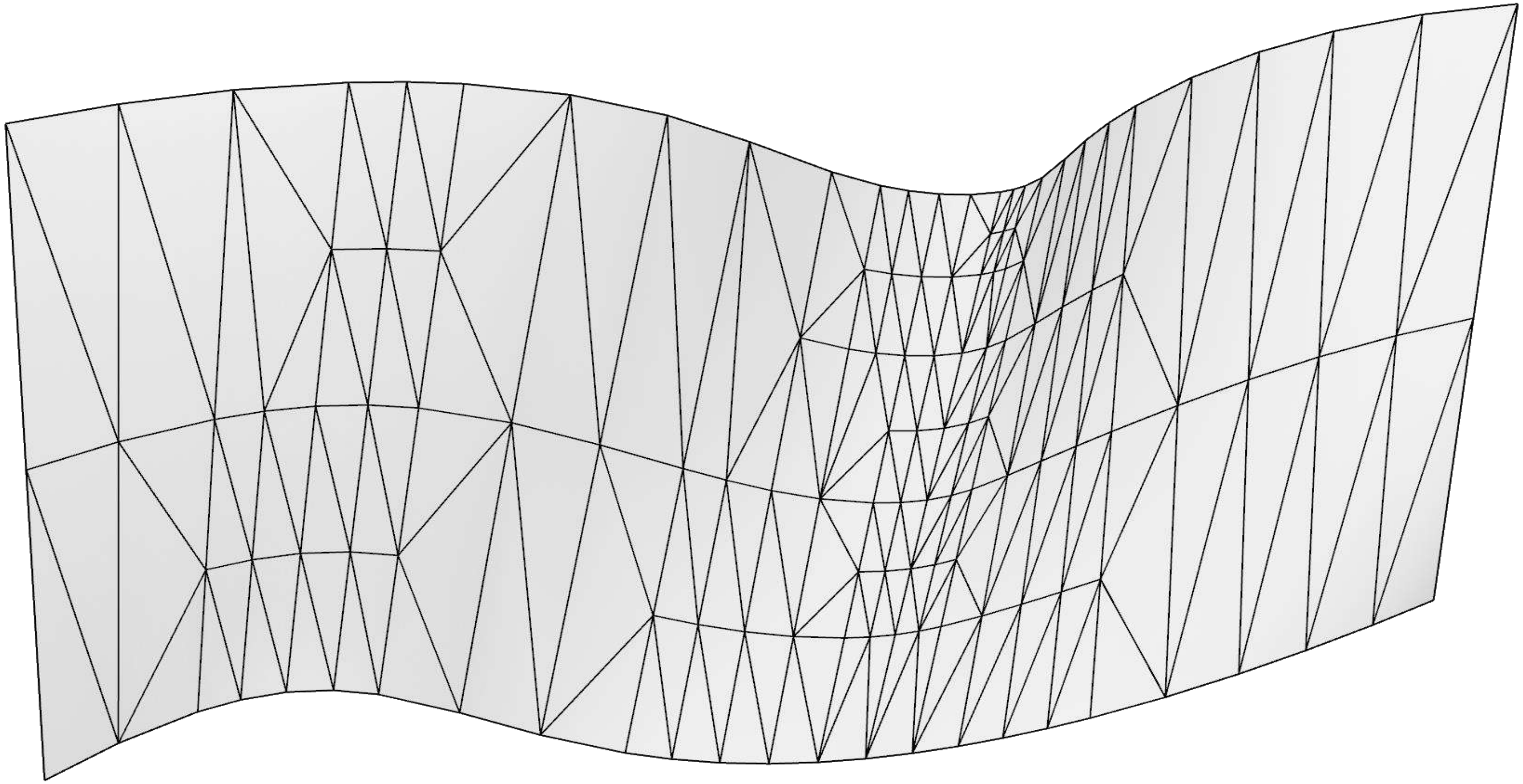
Differential geometry

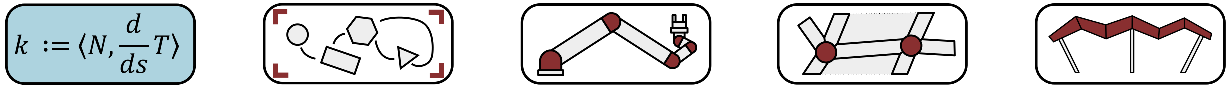




Discretization is the process of transferring continuous functions into distinct elements

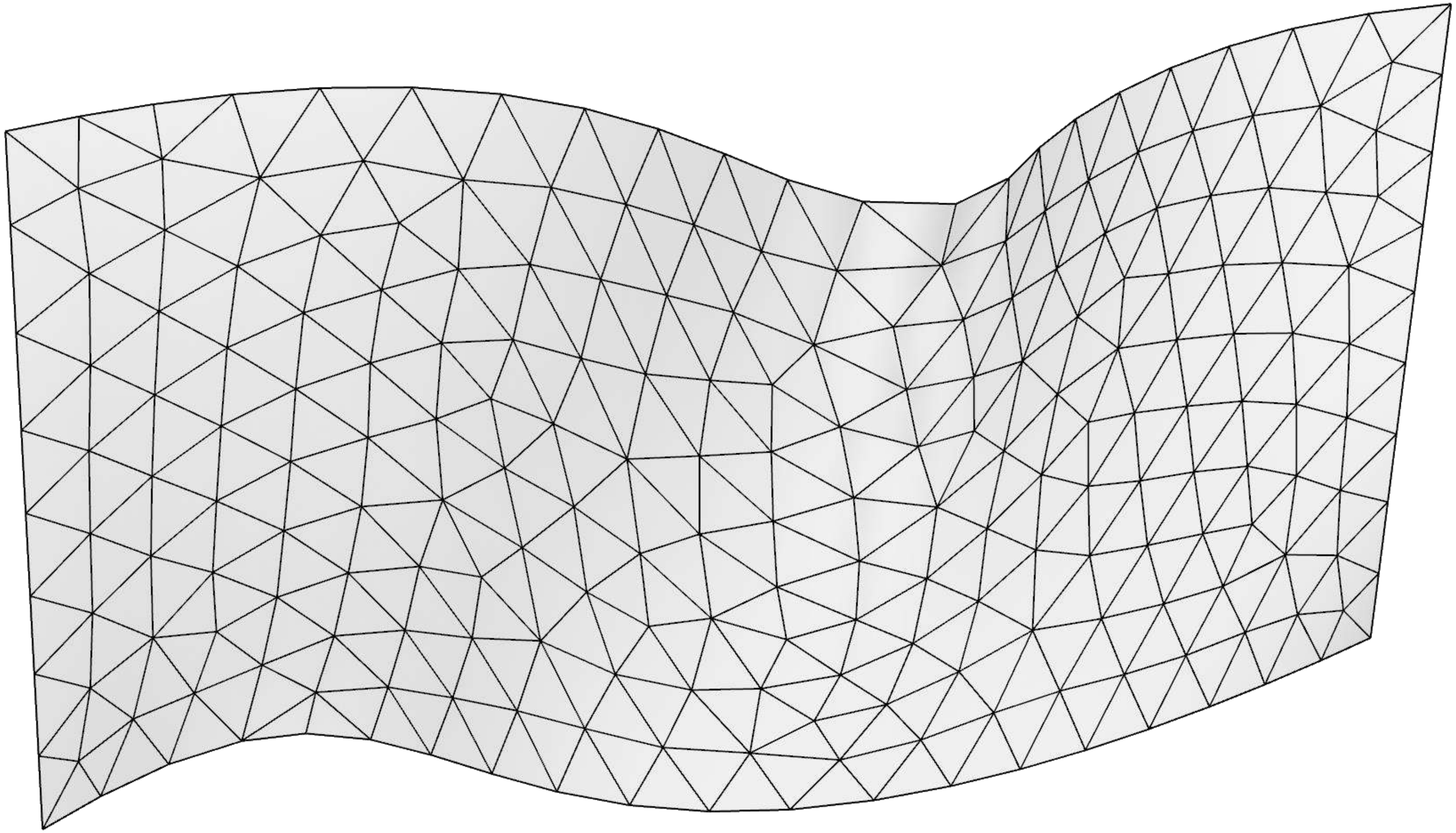
Discrete Geometry

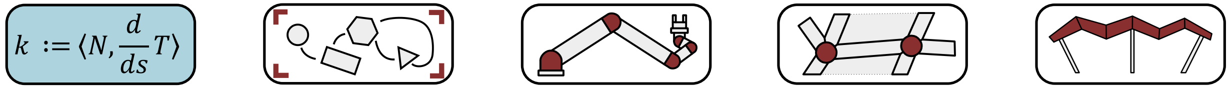




Rationalization can be defined as the approximation of an ideal design surface by a surface which is suitable for fabrication

Rational Geometry



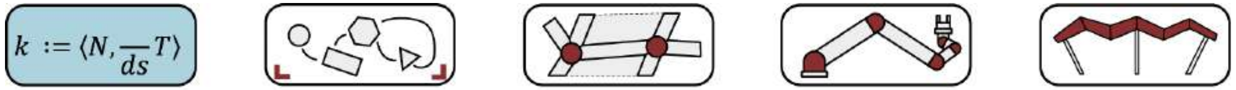


How are freeform shapes constructed?

Nodes, Beams and Panels

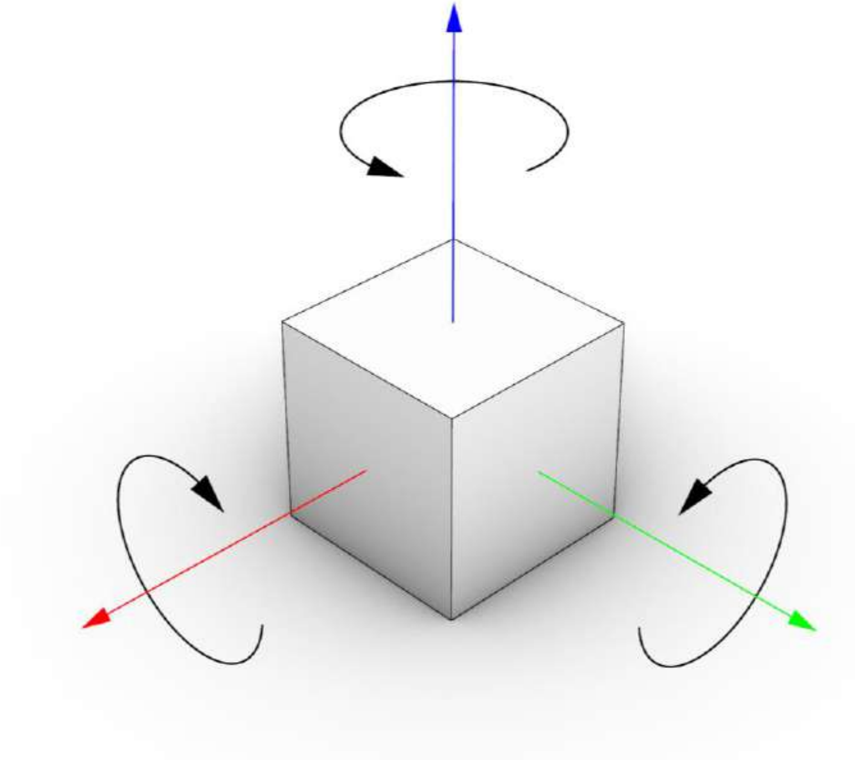
via The Guardian

by Waagner-Biro

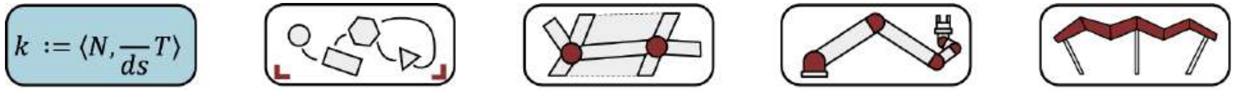


Node

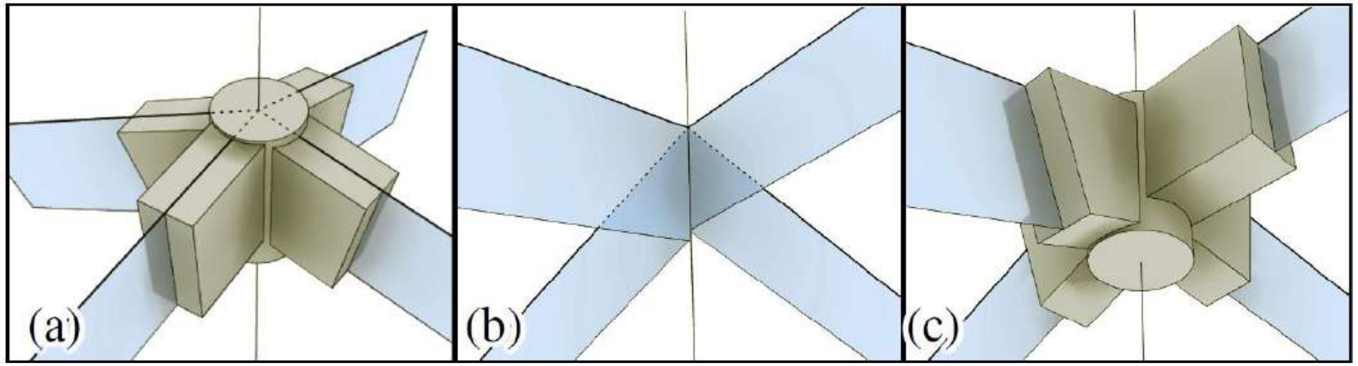
Pottmann H., et al. Geometry of multi-layer freeform structures for architecture, 2007.



Node: 3 Degrees of freedom per connection

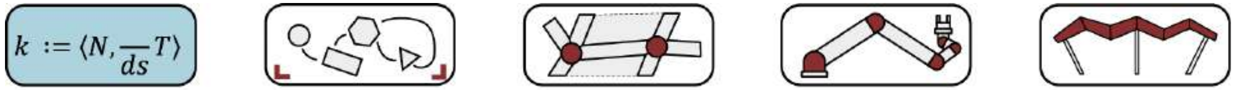


Torsion-free

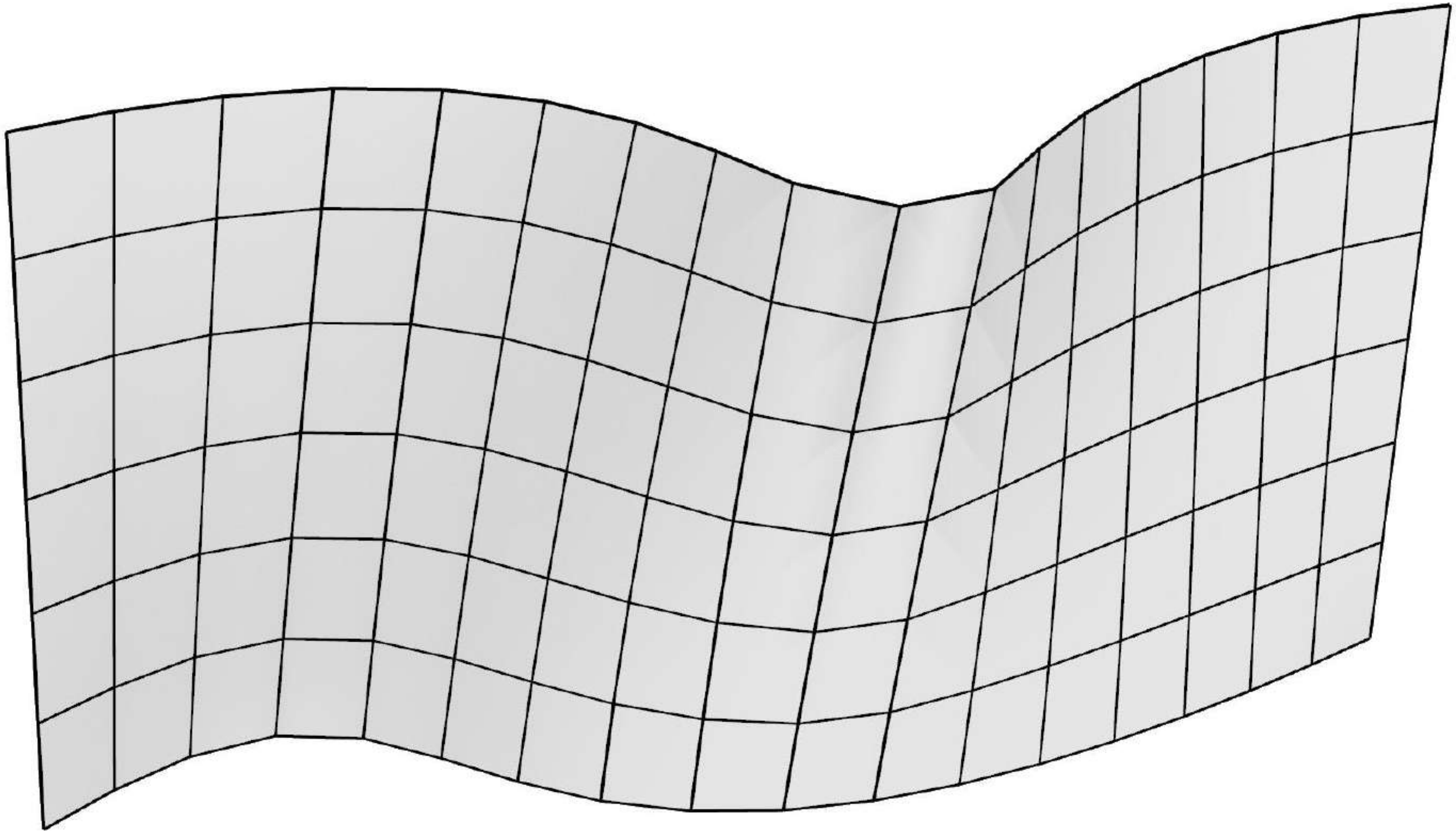


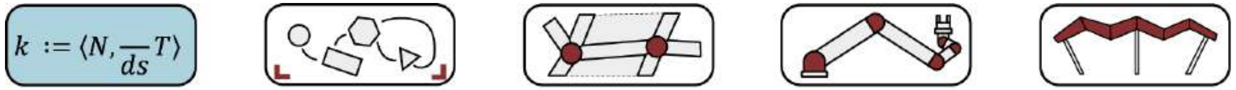
Triangle meshes – the most basic, convenient, and structurally stable way of representing a smooth shape in a discrete way – do not support desirable properties of meshes relevant to building construction (most importantly, "torsion-free" nodes)

Pottman H. et al., Architectural Geometry, 2007.

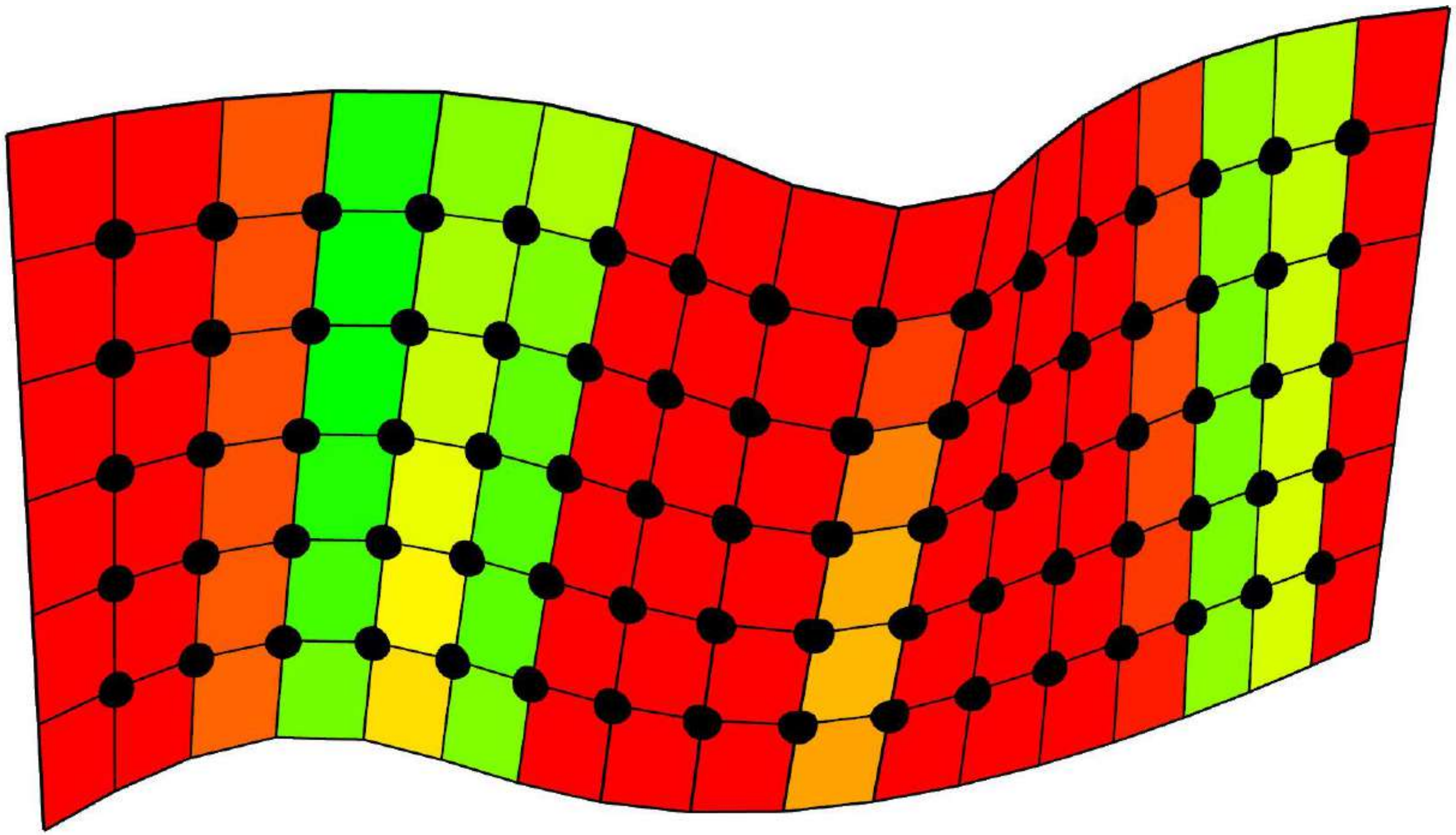


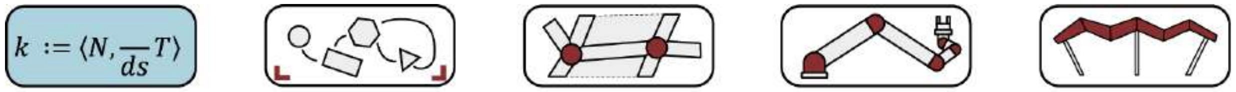
Quadrangular rationalization



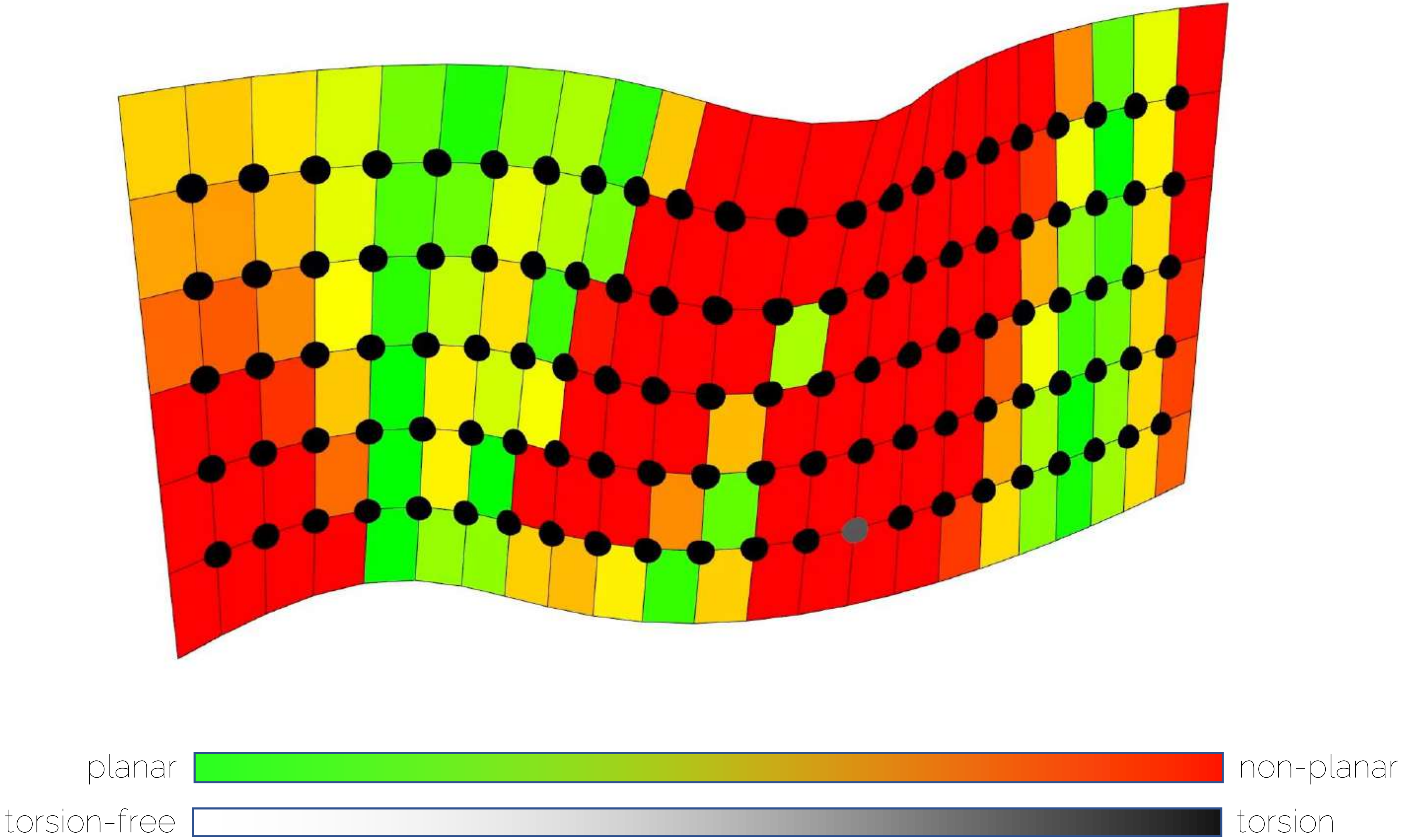


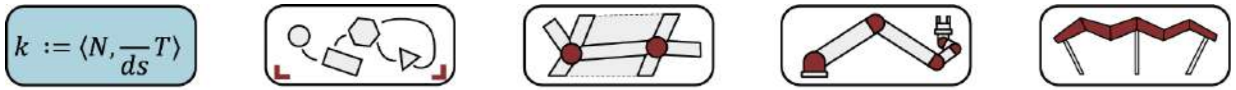
Quadrangular rationalization



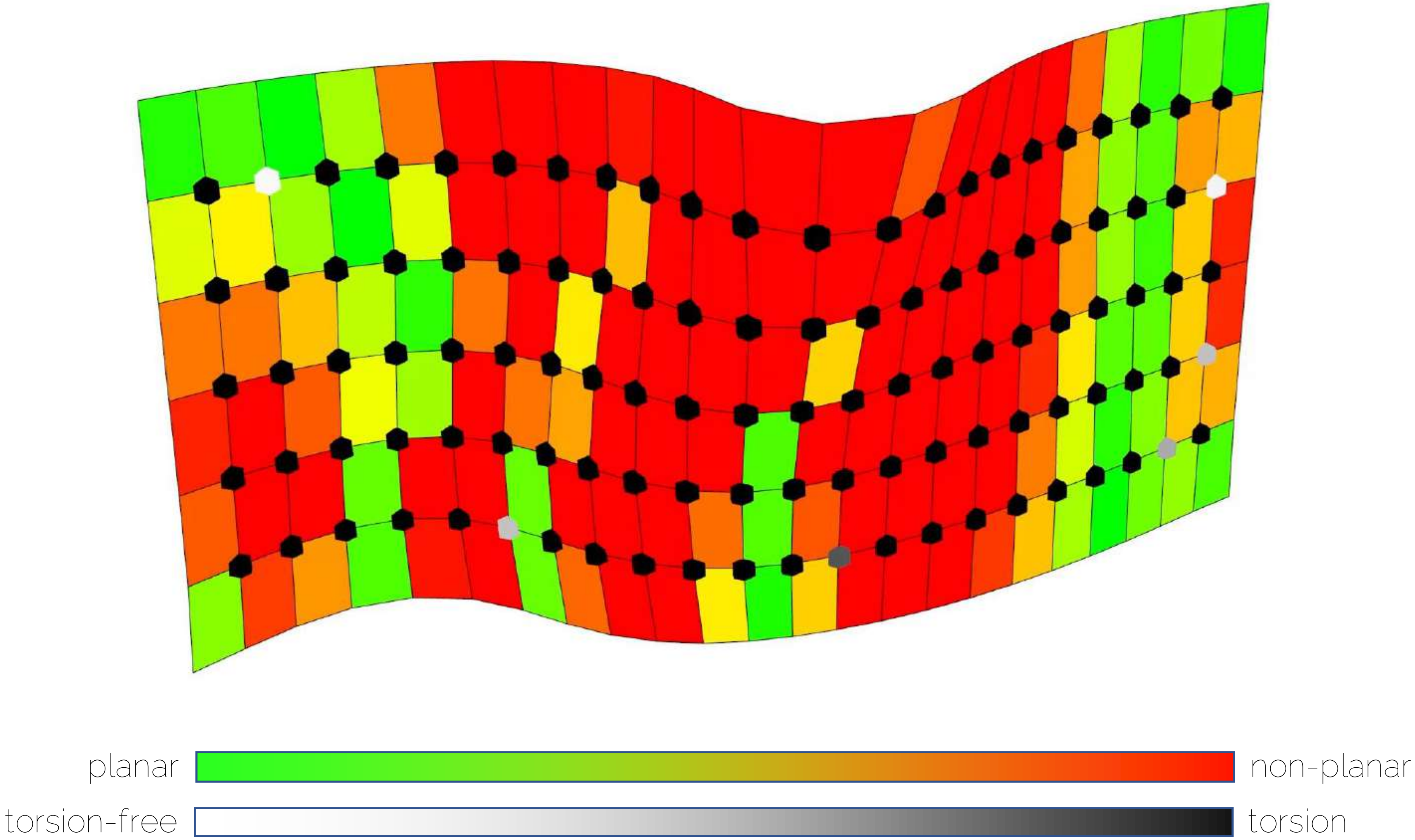


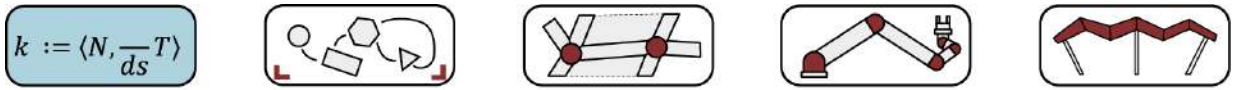
Mesh perturbation: planarize





Mesh perturbation: balanced pullback





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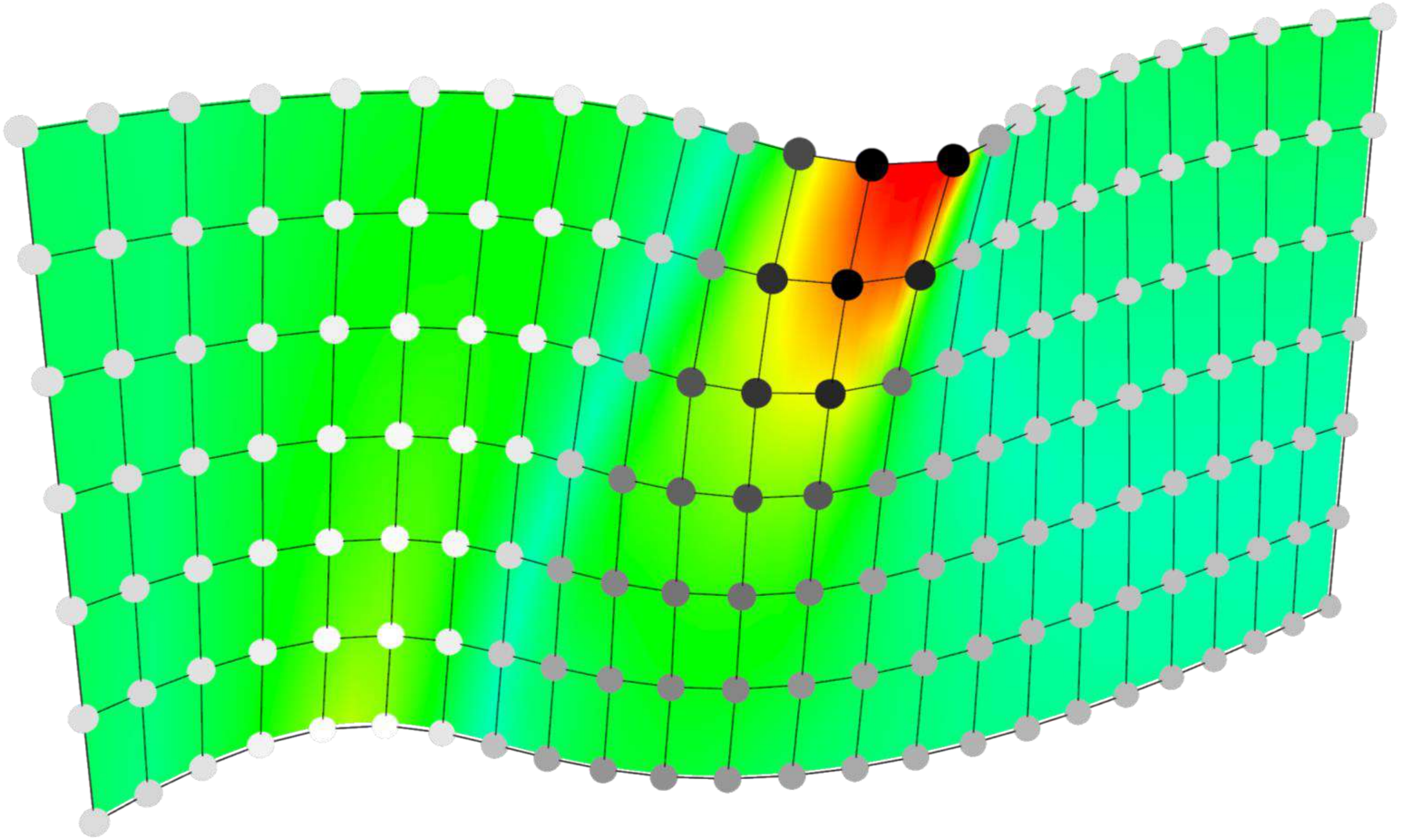
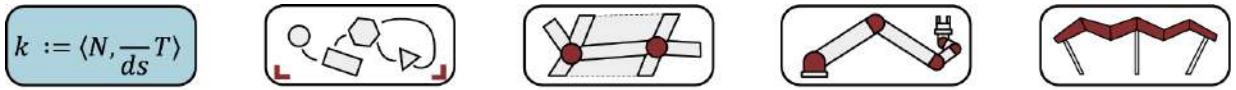


low curvature — high curvature

low pullback — high pullback



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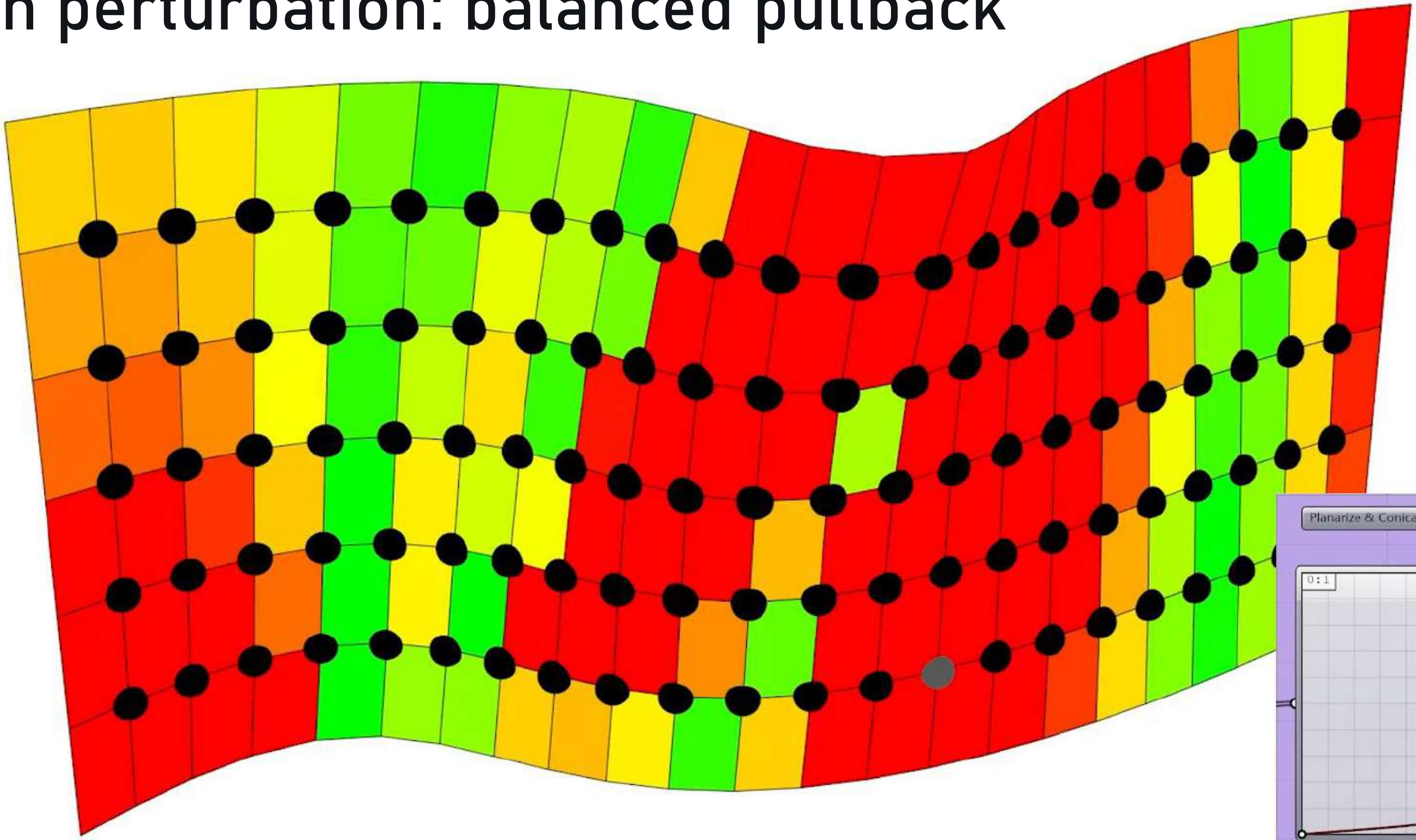
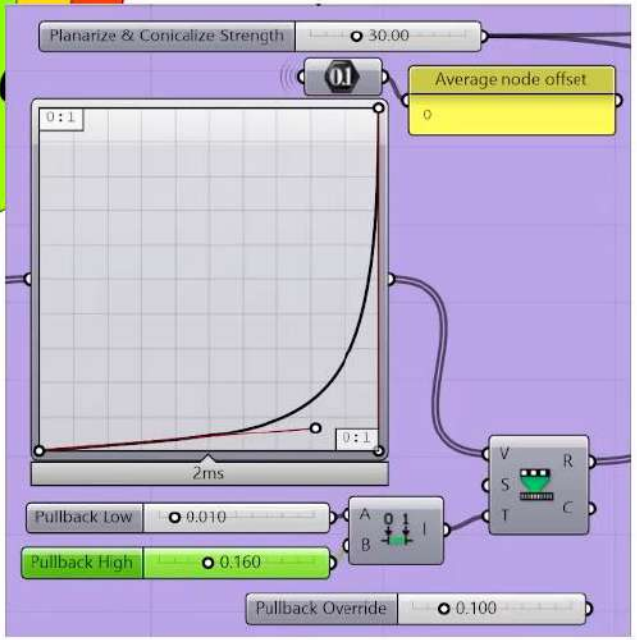
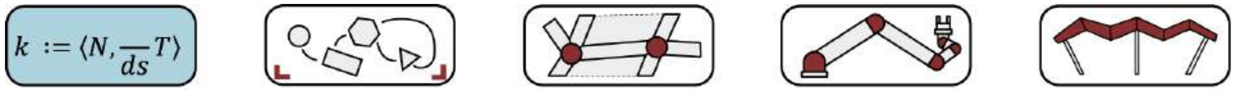




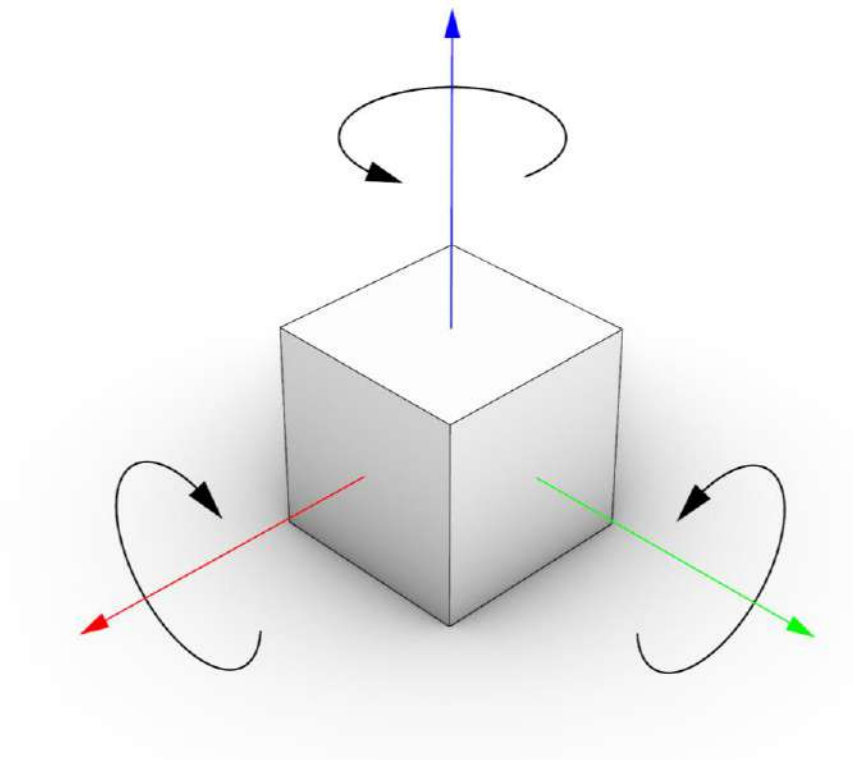


How can optimal rationalizations of freeform building facades be determined?

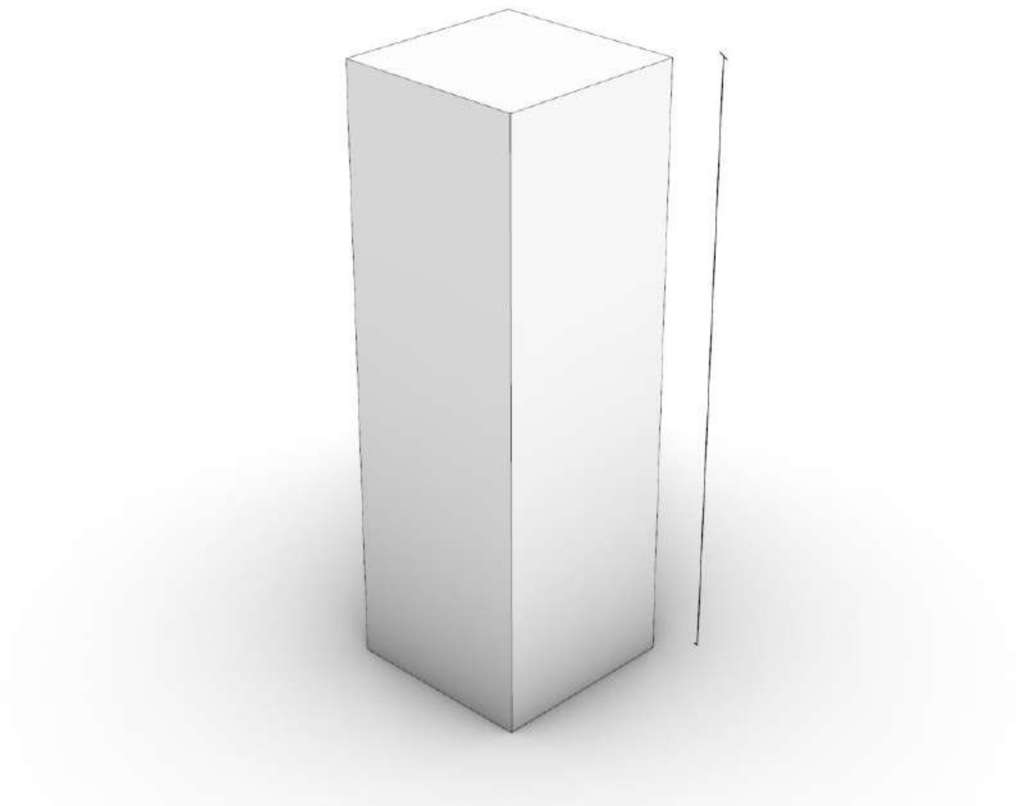
4 Design Boundaries

How can theory on mesh rationalization be applied to define the design requirements and boundaries of a reusable nodes and beams system for freeform building facades?

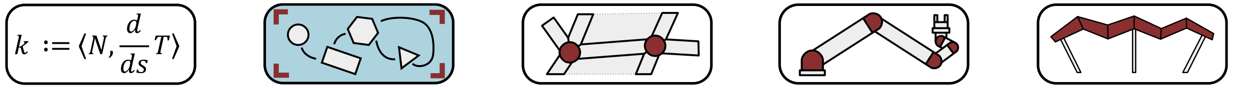
Internal parameters



Node: 3 Degrees of freedom per connection

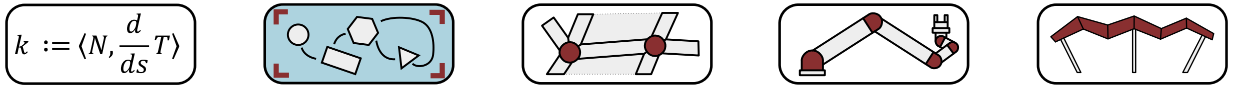


Beam: Length

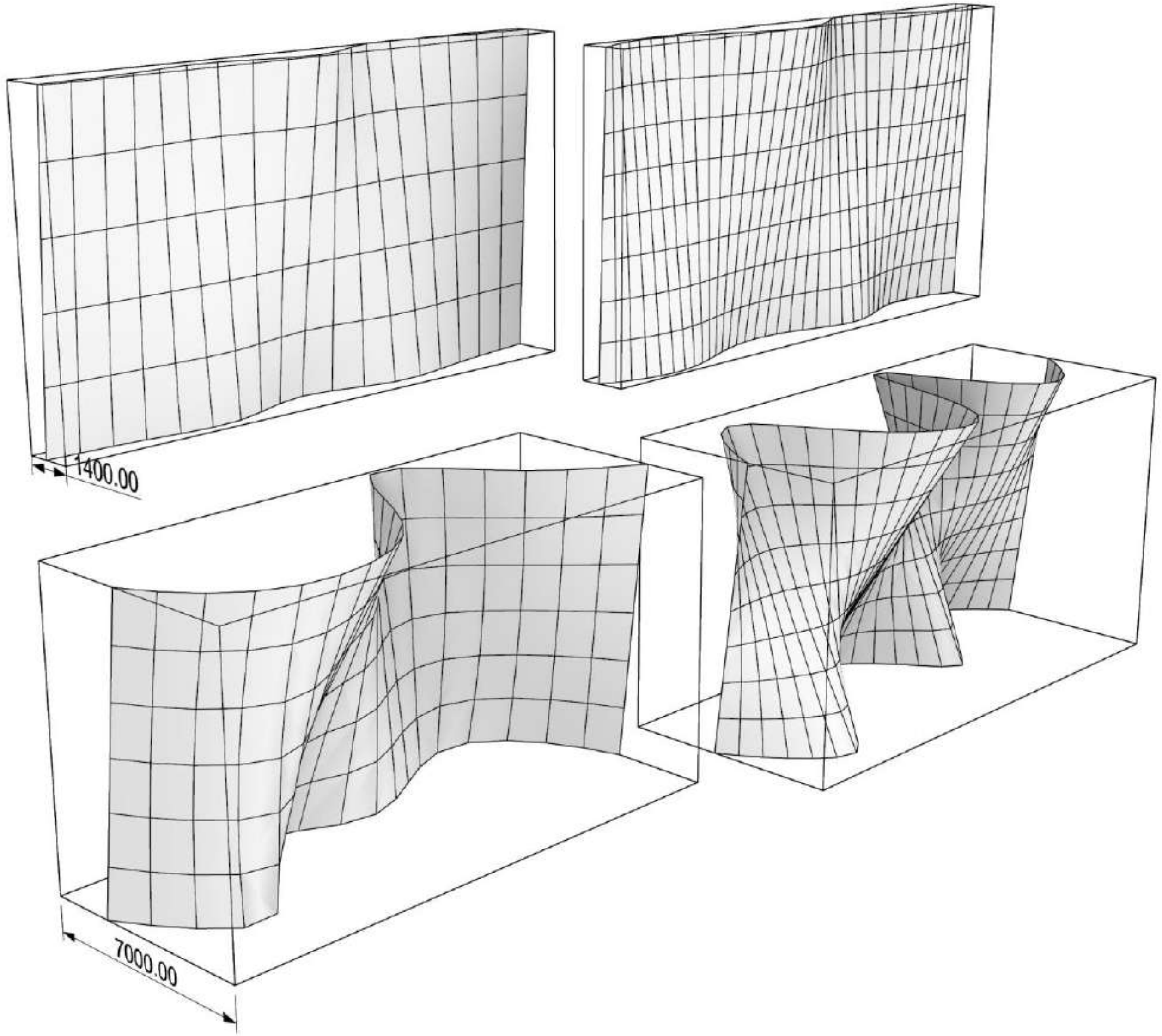


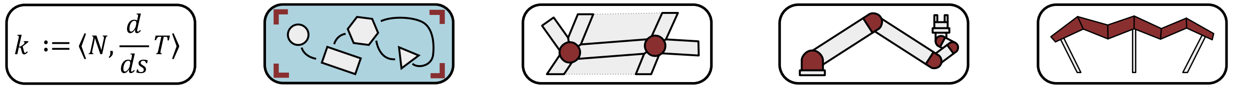
Reuse – two hypotheticals

element library ⟷ variable elements

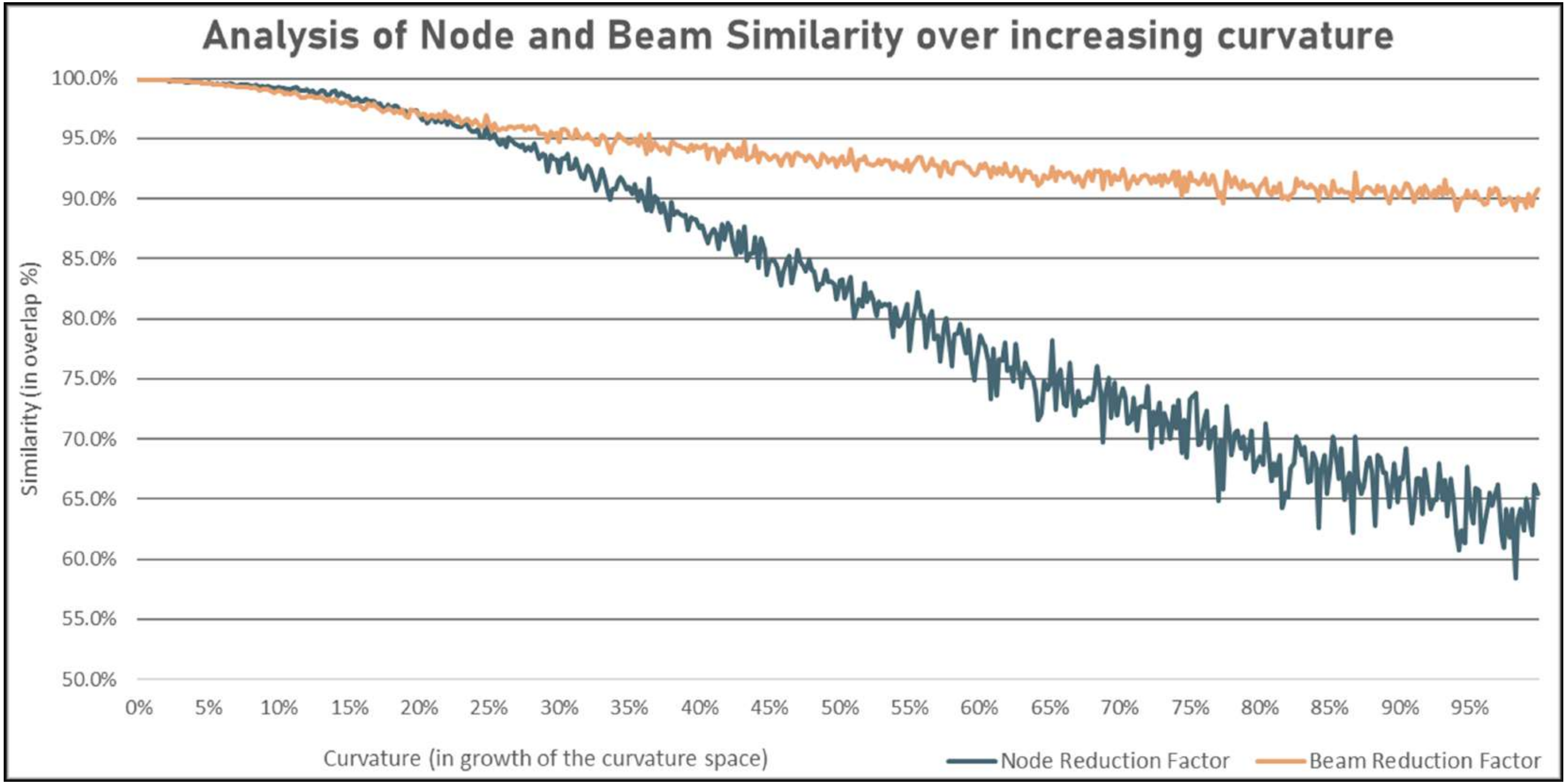


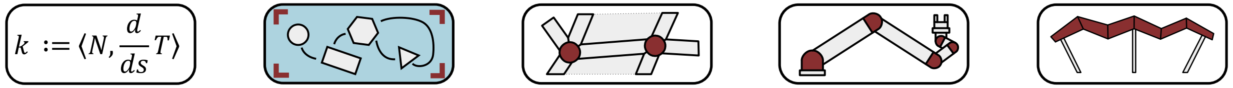
Element overlap - shape generation





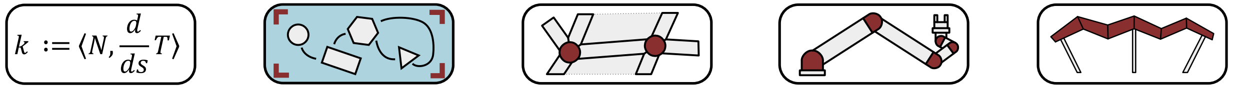
Element overlap - result





Conclusion

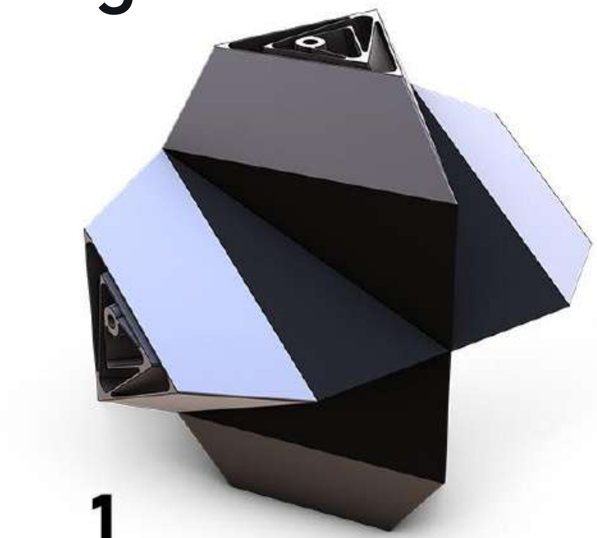
variable nodes ⟷ library beams



5 Node Design

How can a reusable node & beam system for freeform building facades be designed?

Explorative design

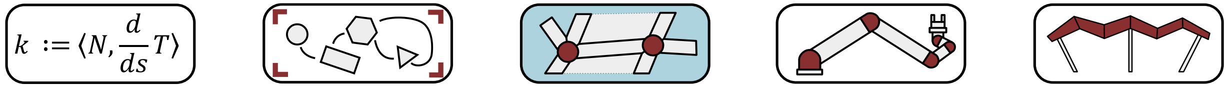


1

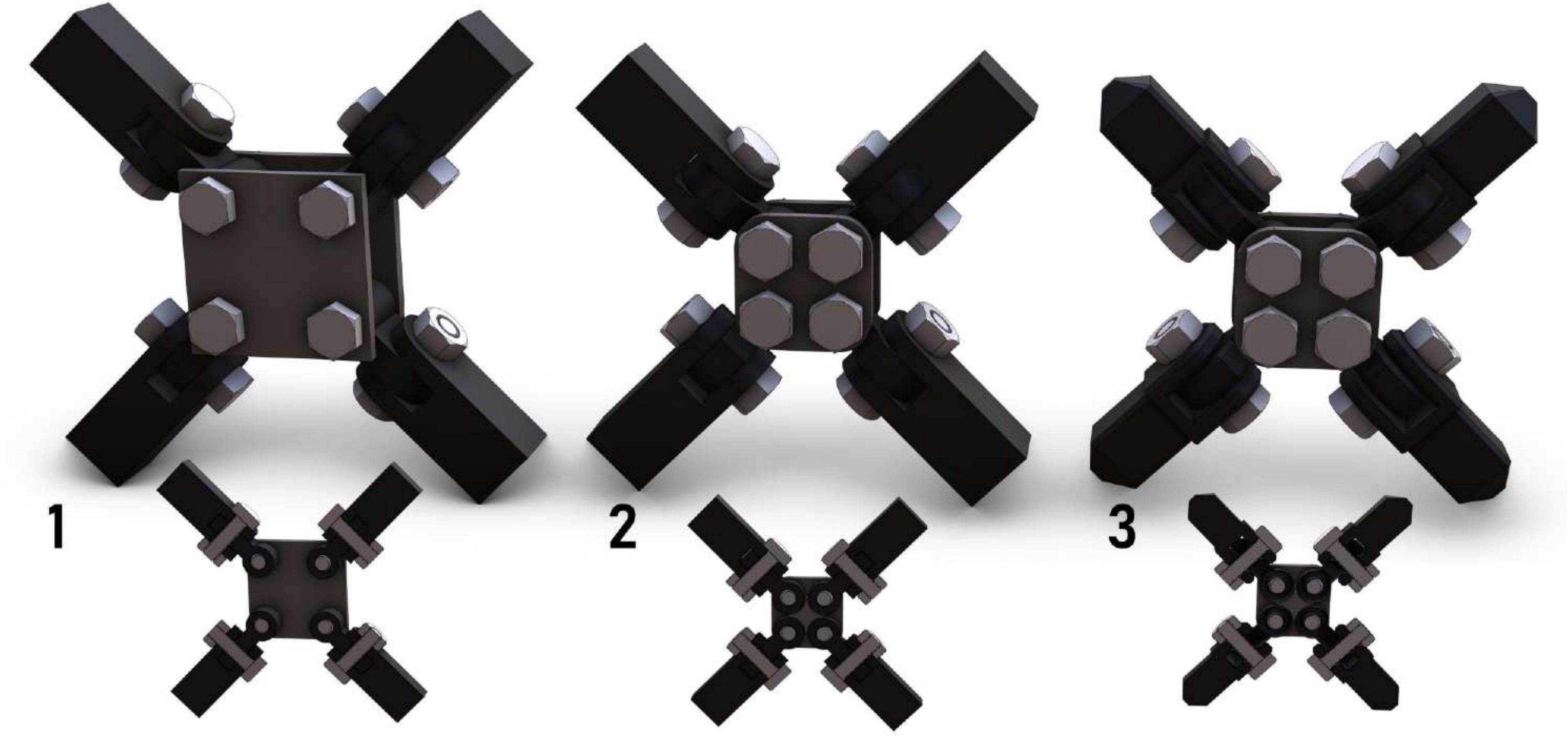
2

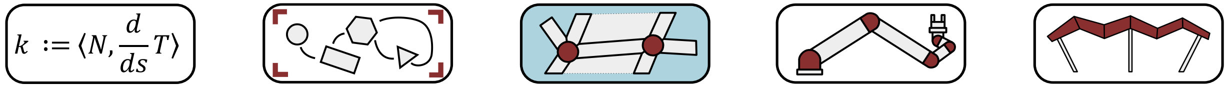
3

4

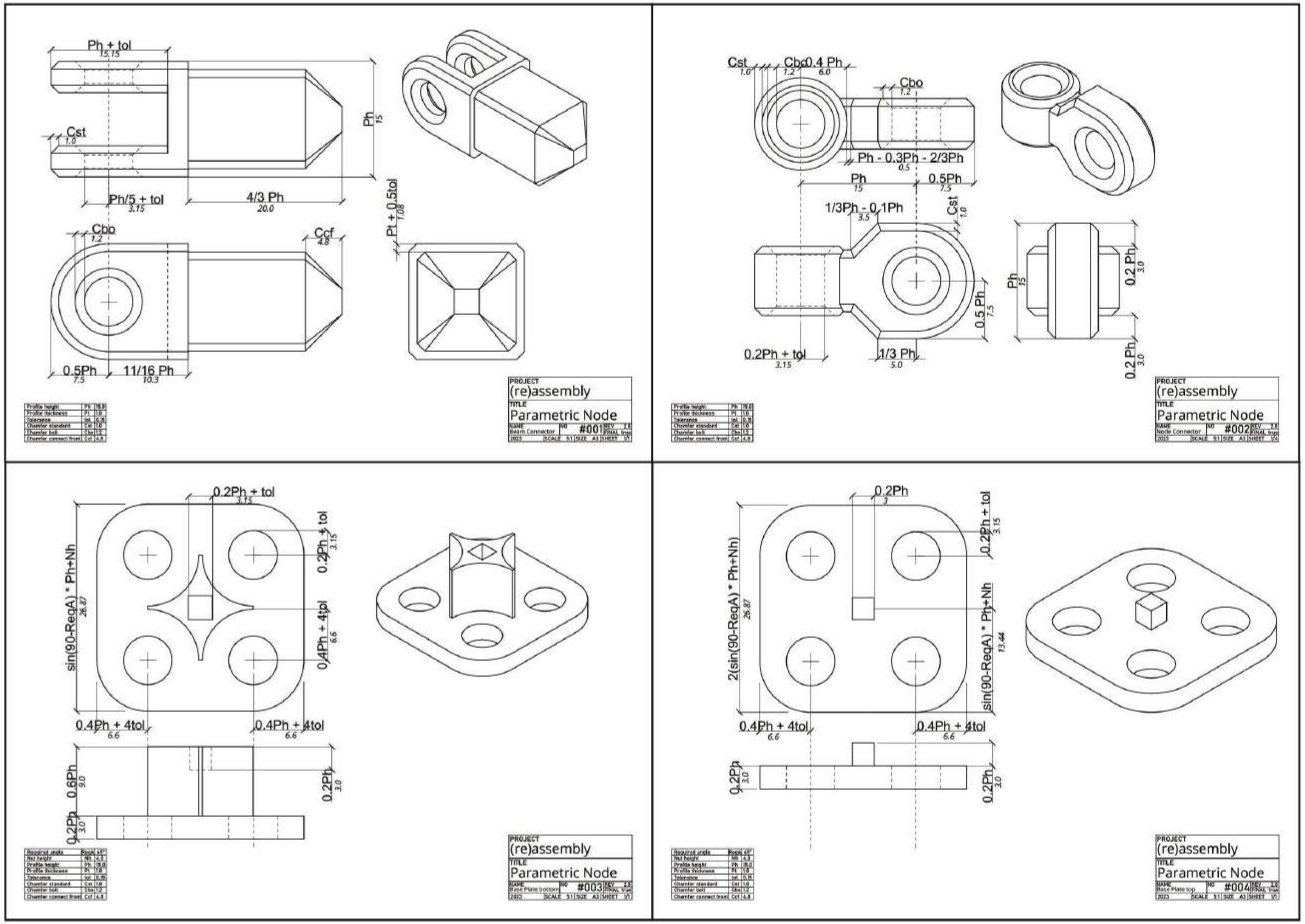


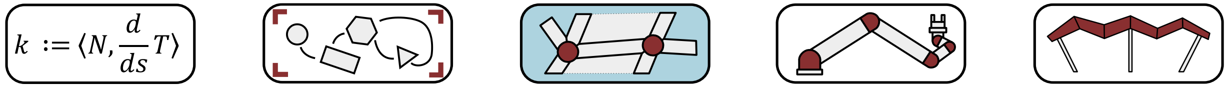
Iterative design



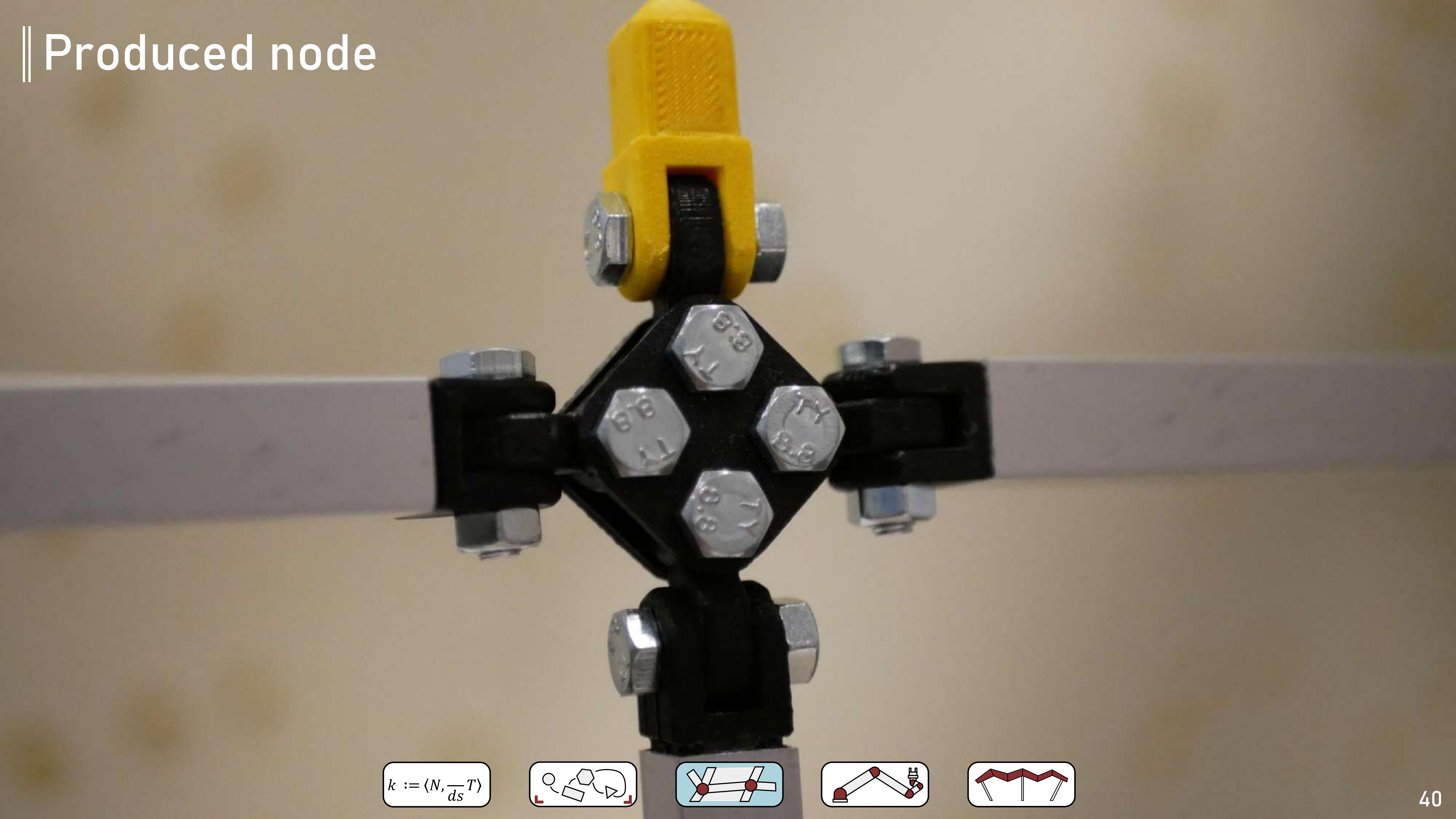


Parametric design

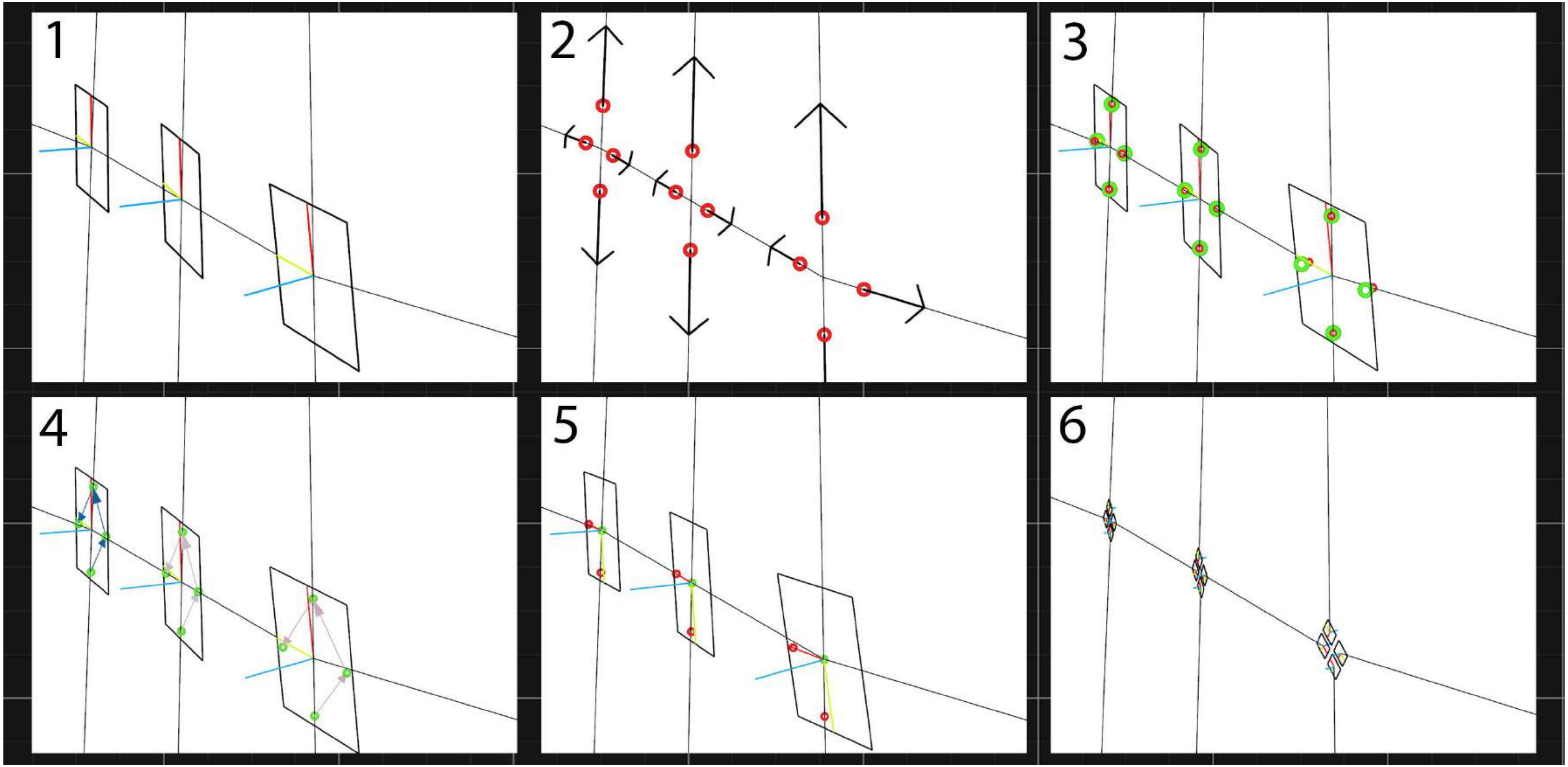


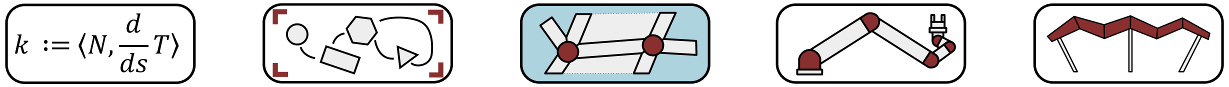


Produced node

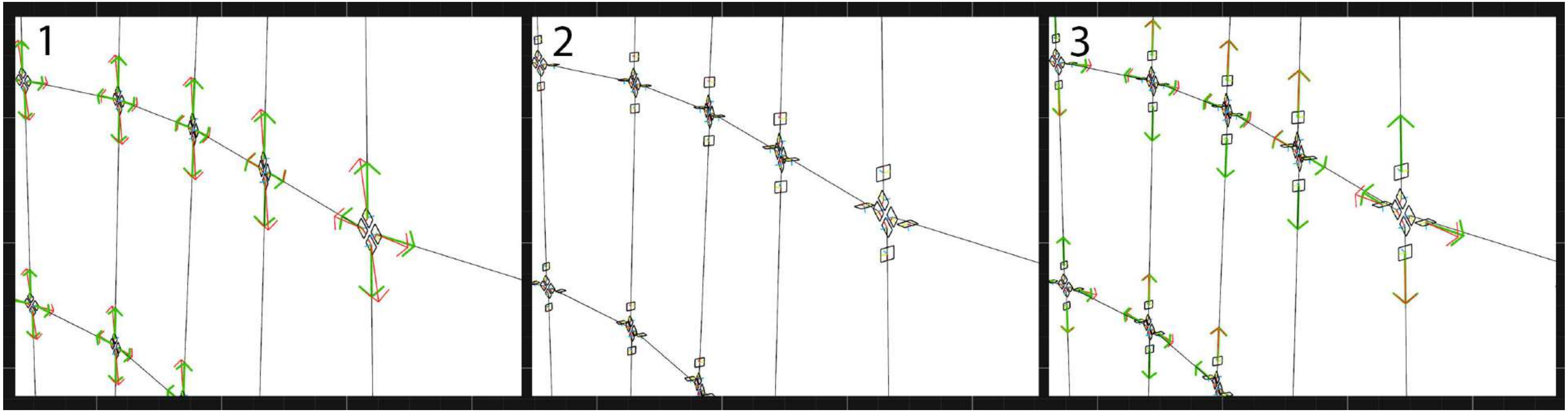


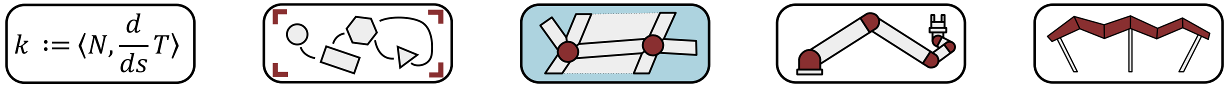
Computational placement – frame generation



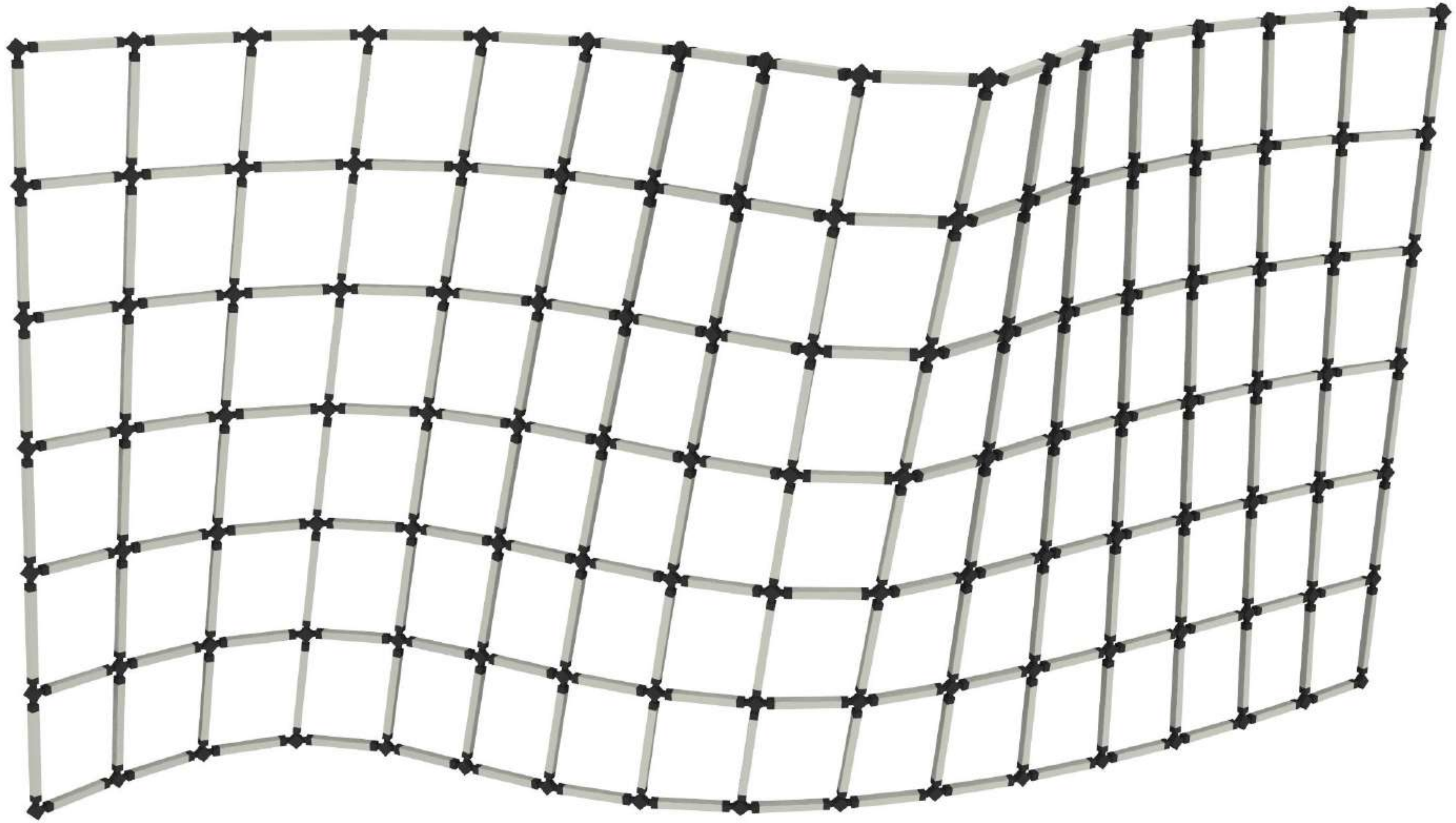


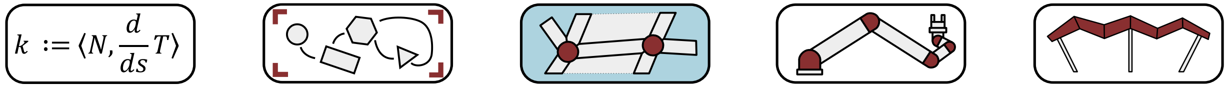
Computational placement – angle calculation



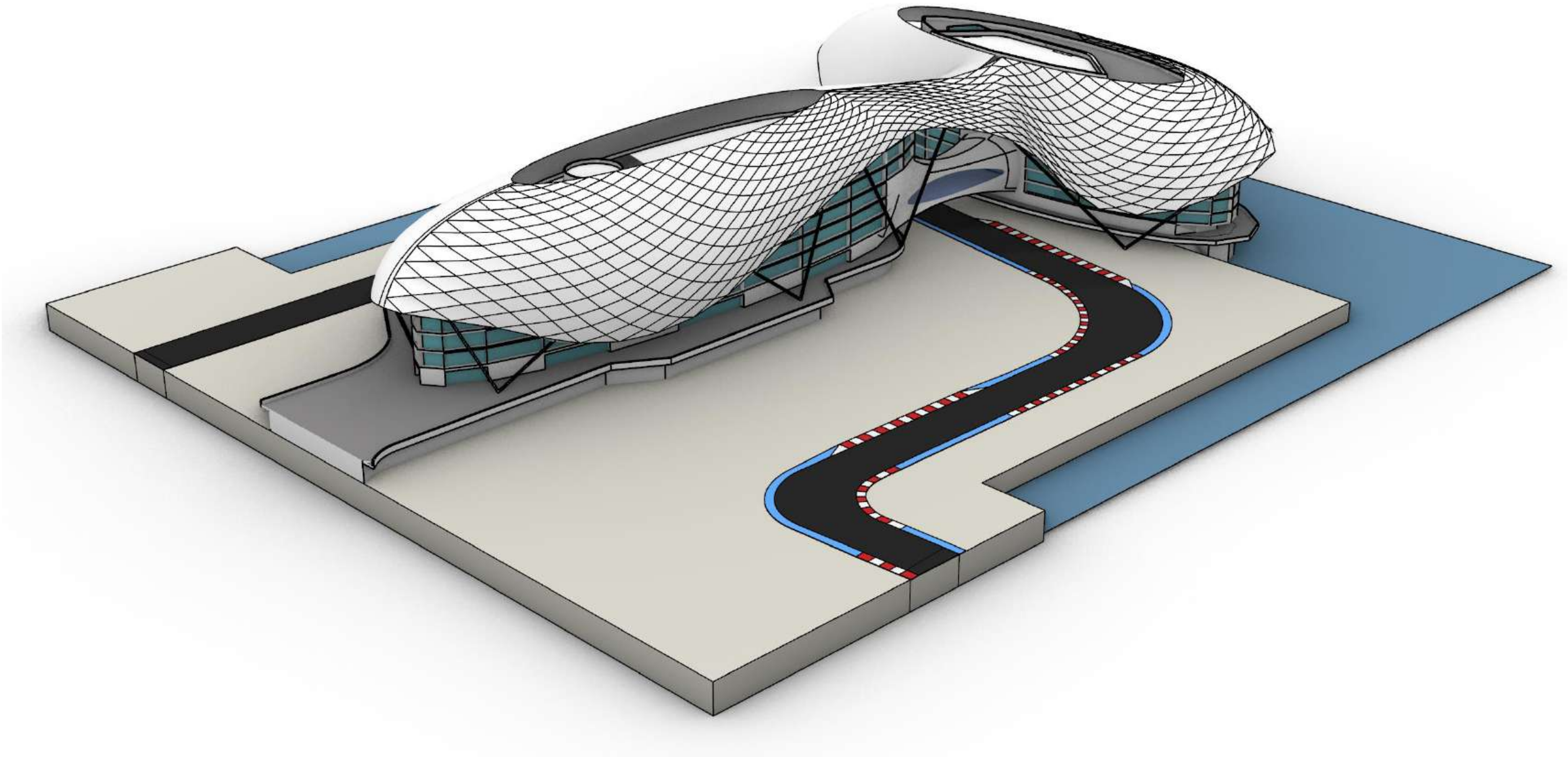


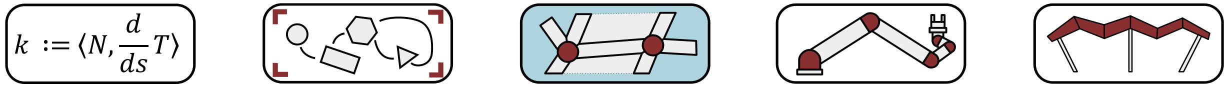
Computational placement





Case study – Yas Marina Hotel





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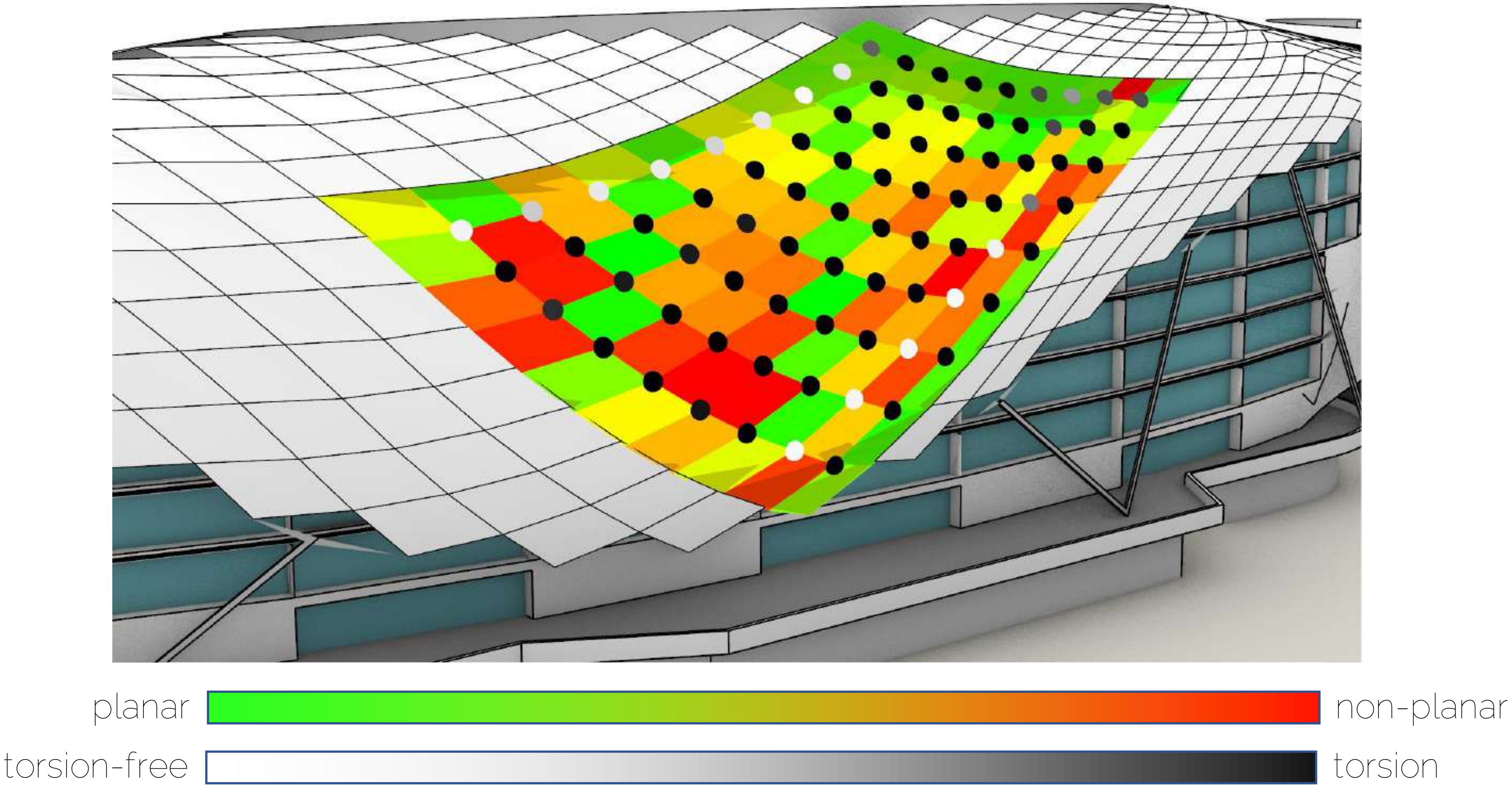

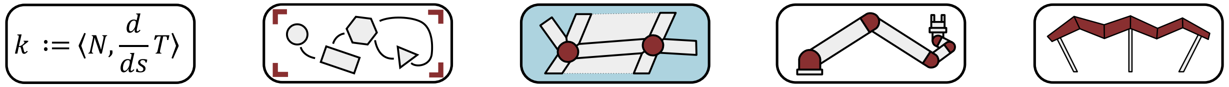

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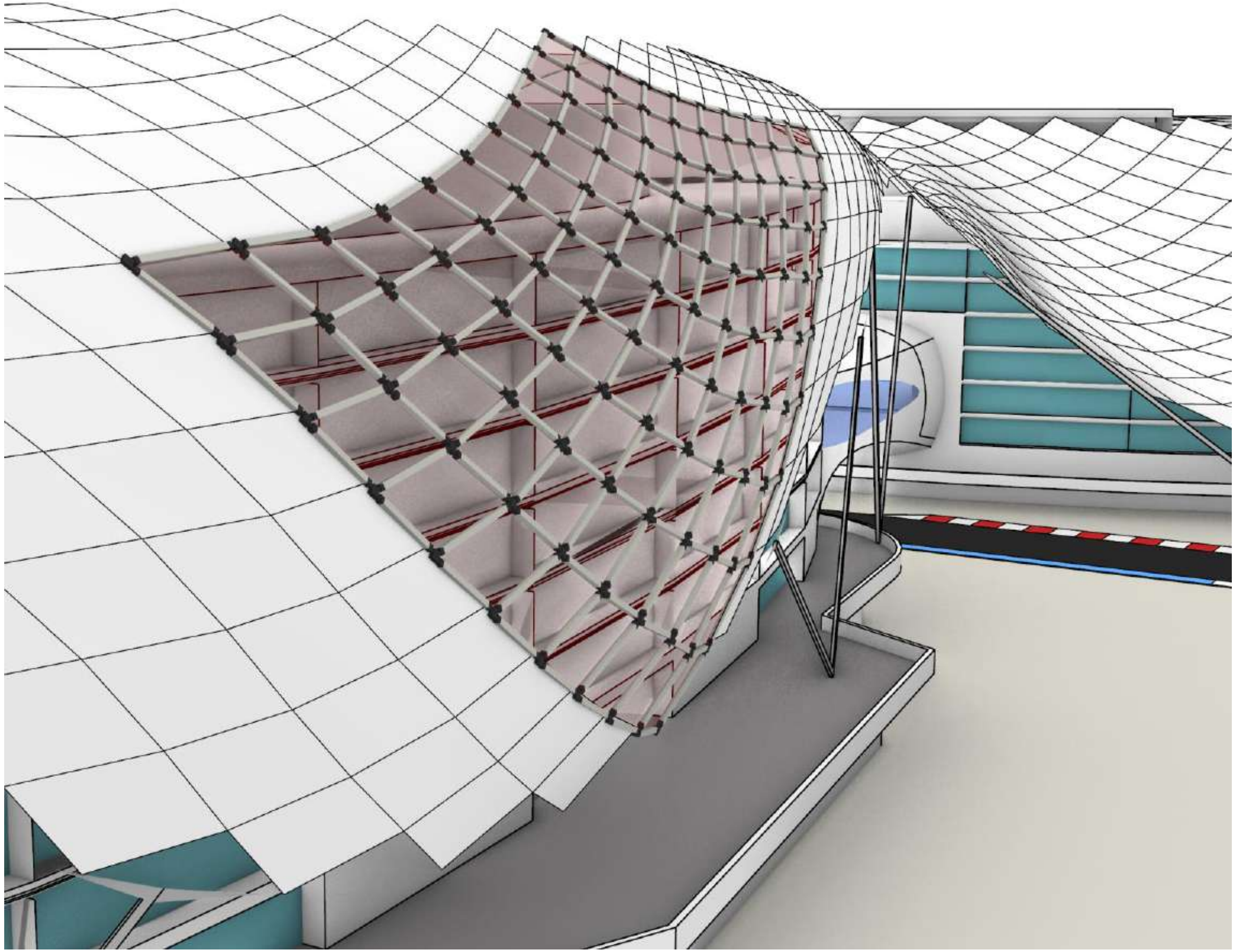

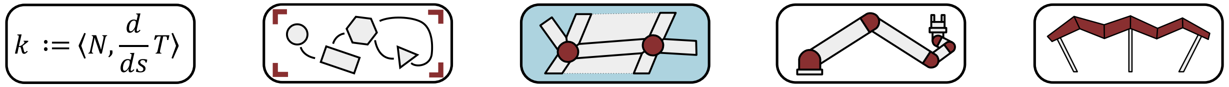

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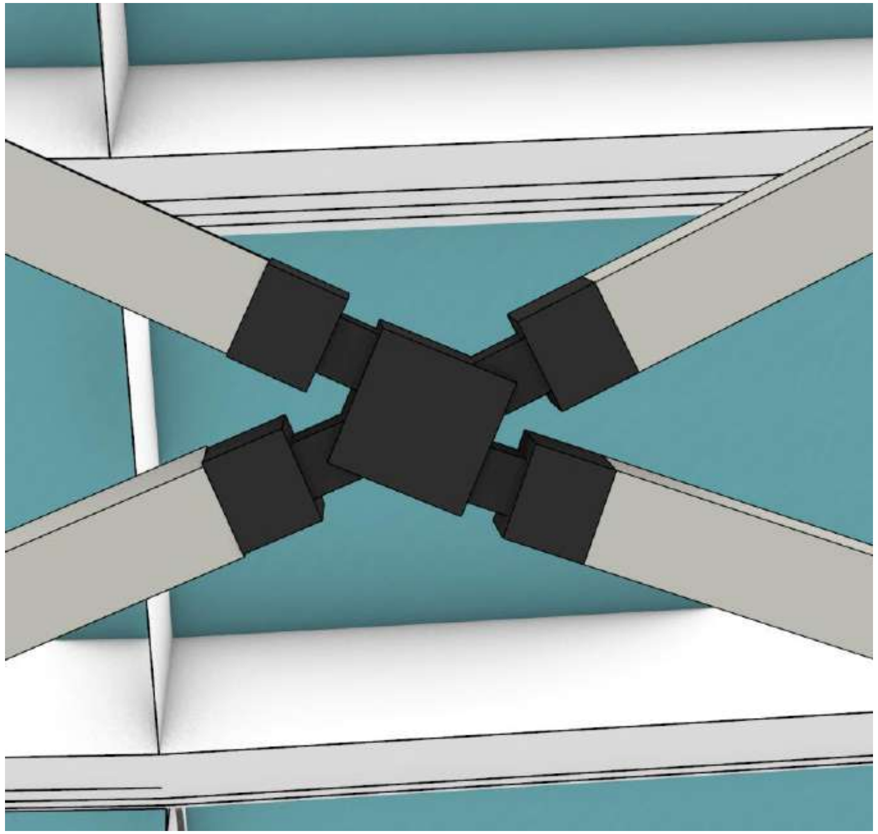
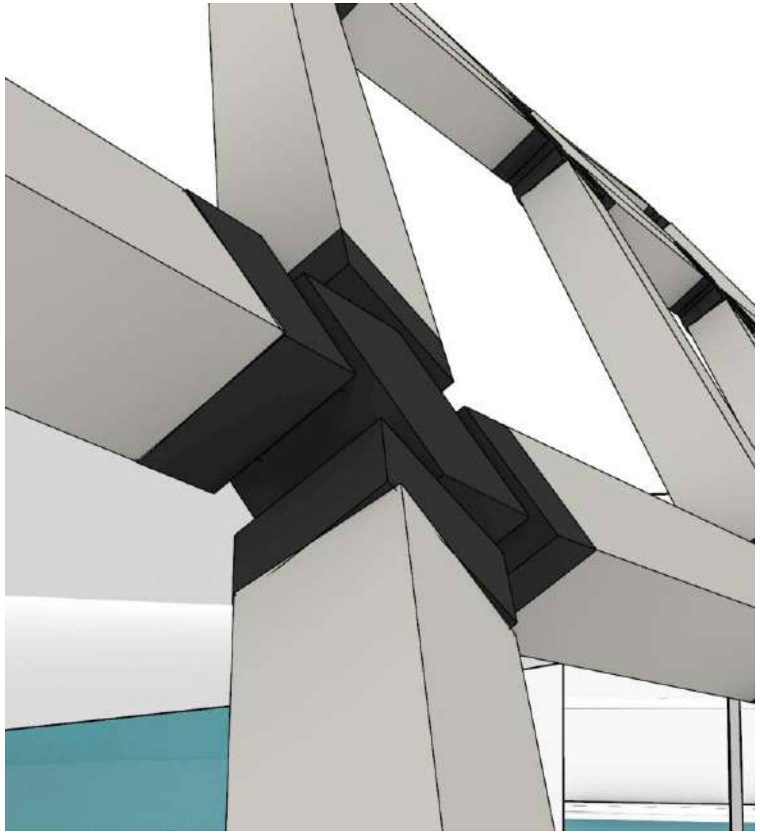
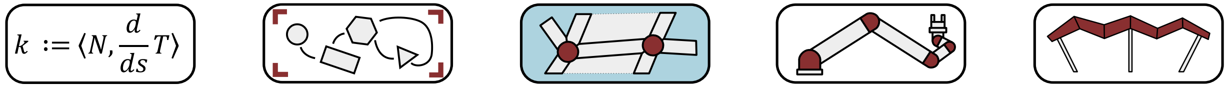


Diamond Grid



Torsion



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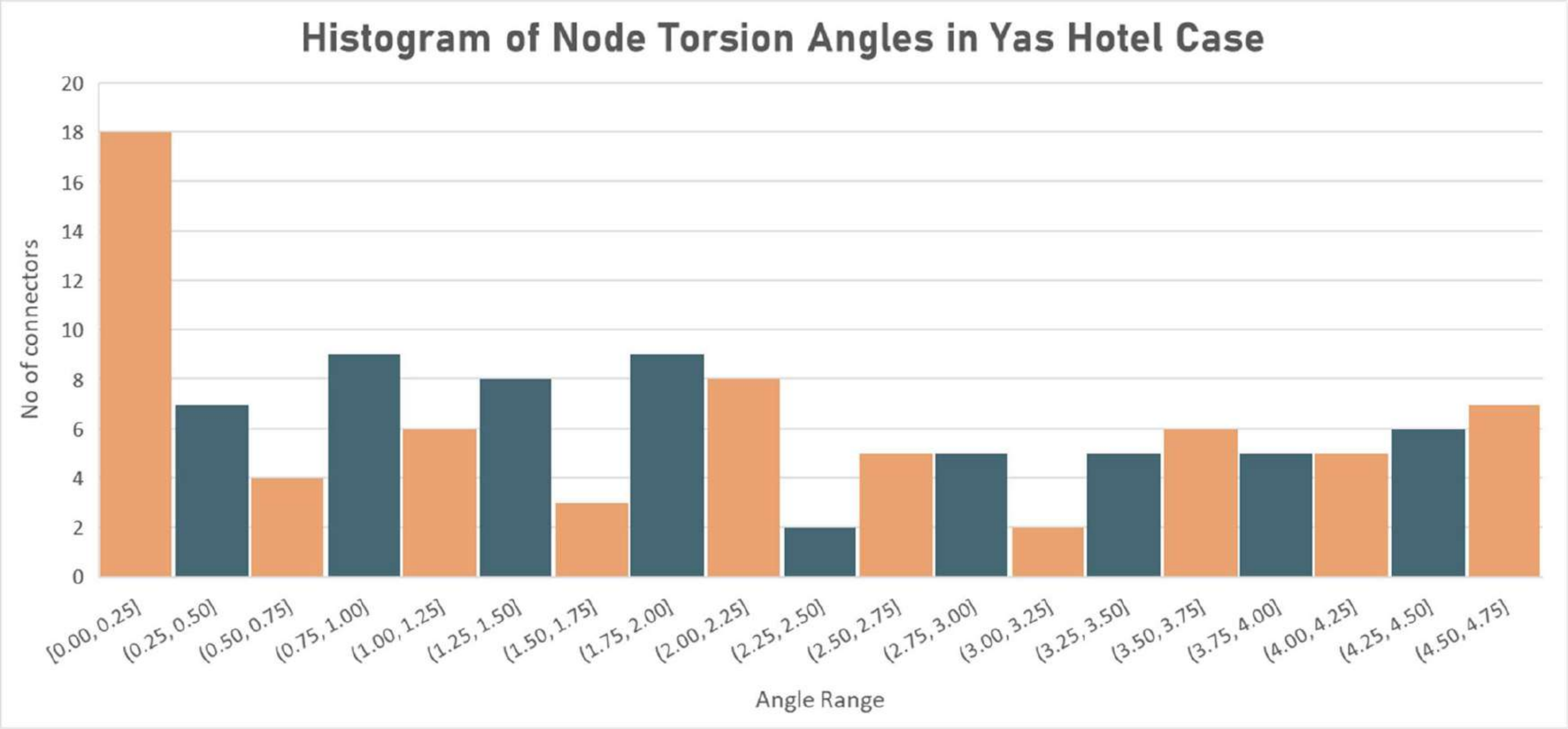
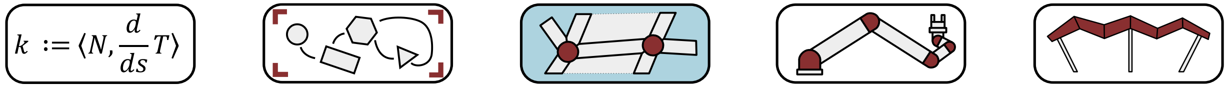




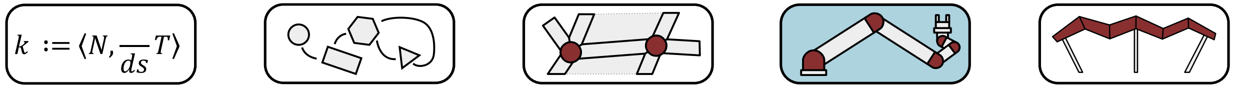
Can small amounts of torsion be compensated by tolerances and flex in the system?

6 Robotic Assembly

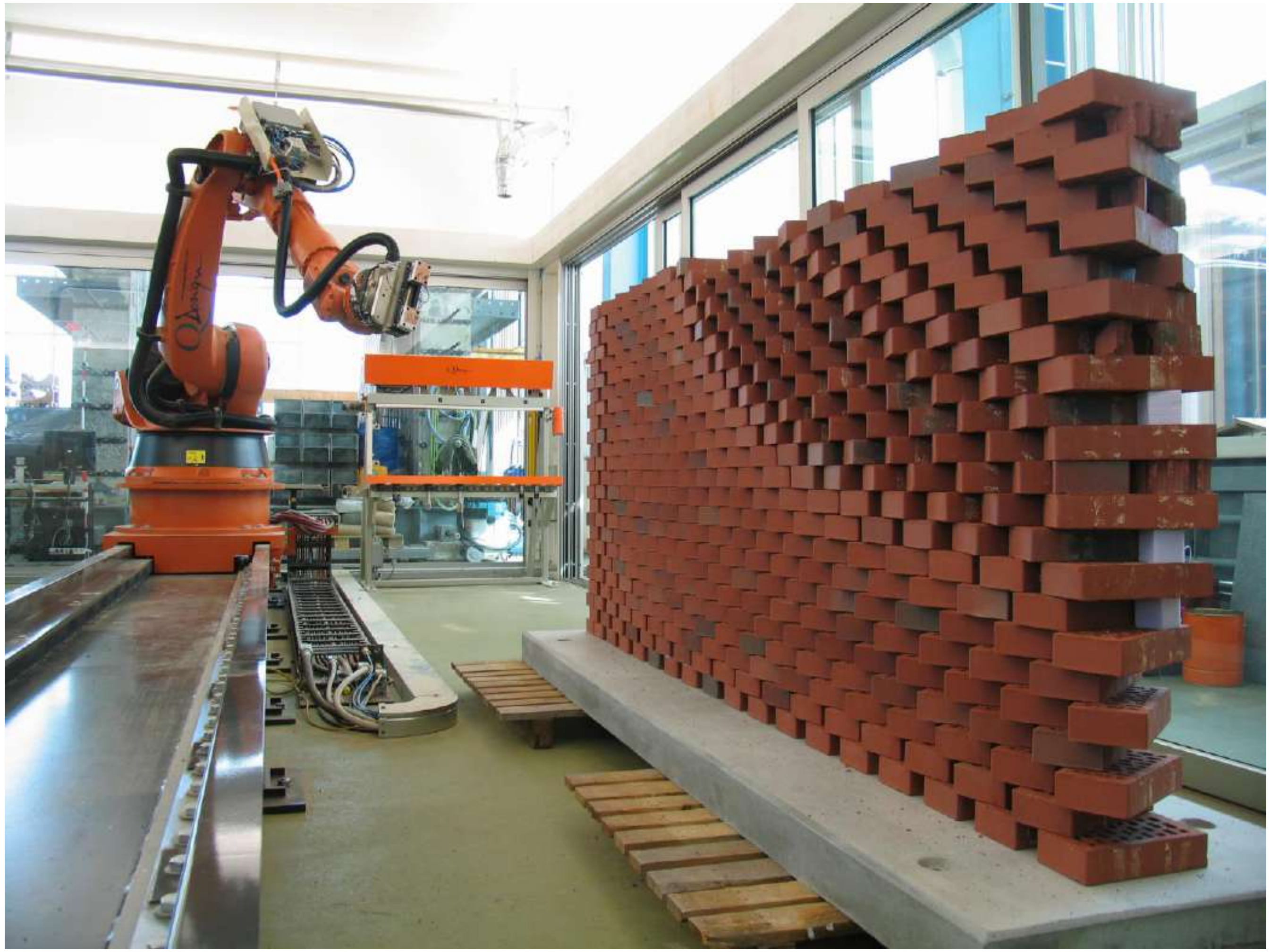
What is the state of the art in robotic construction and how can it be used to automatically assemble a system of reusable nodes and beams in freeform building facades?

Literature review

	LVL 1: Simple Placing	LVL 2: Complex Systems	LVL 3: Smart Instructions	LVL 4: Diversified Agents
Movement	stationary & linear →	XYZ Gantry →	free →	system integrated
Sensing	sensorless →	force limiting →	computer vision →	swarm communication
Solving	interpolation →	collision free →	task planning →	multi robot
Operation	pick & place →	system building →	symbolic instructions →	heterogeneous

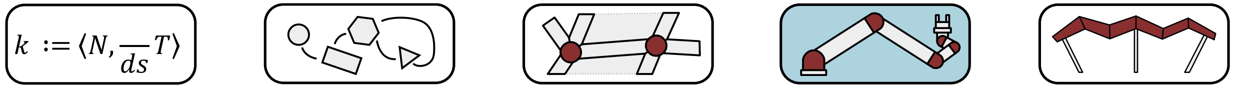


lvl 1: Simple Placing

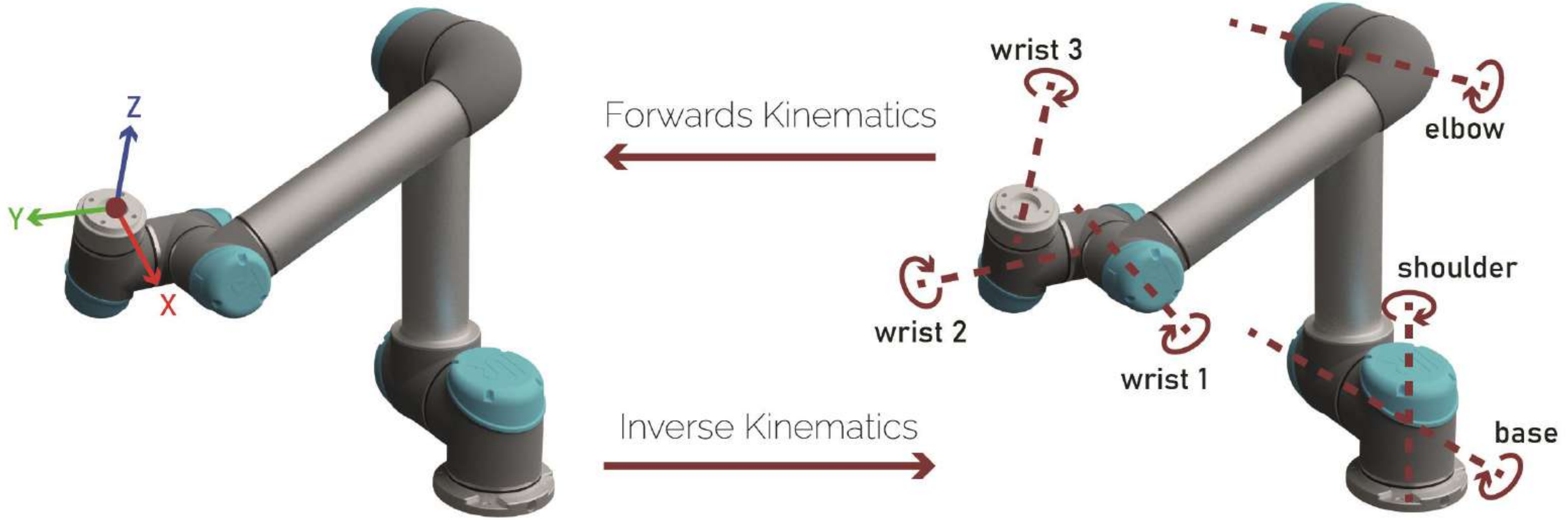


Bonwetsch T., et al. The informed wall: Applying additive digital fabrication techniques on architecture, 2006.

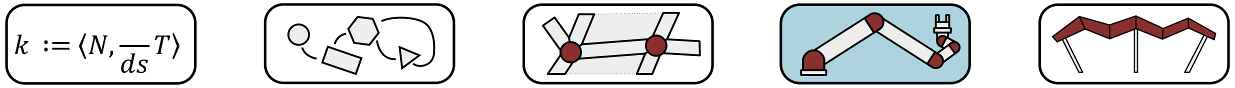
Movement: stationary & linear Sensing: sensorless Solving: interpolation Operation: pick & place



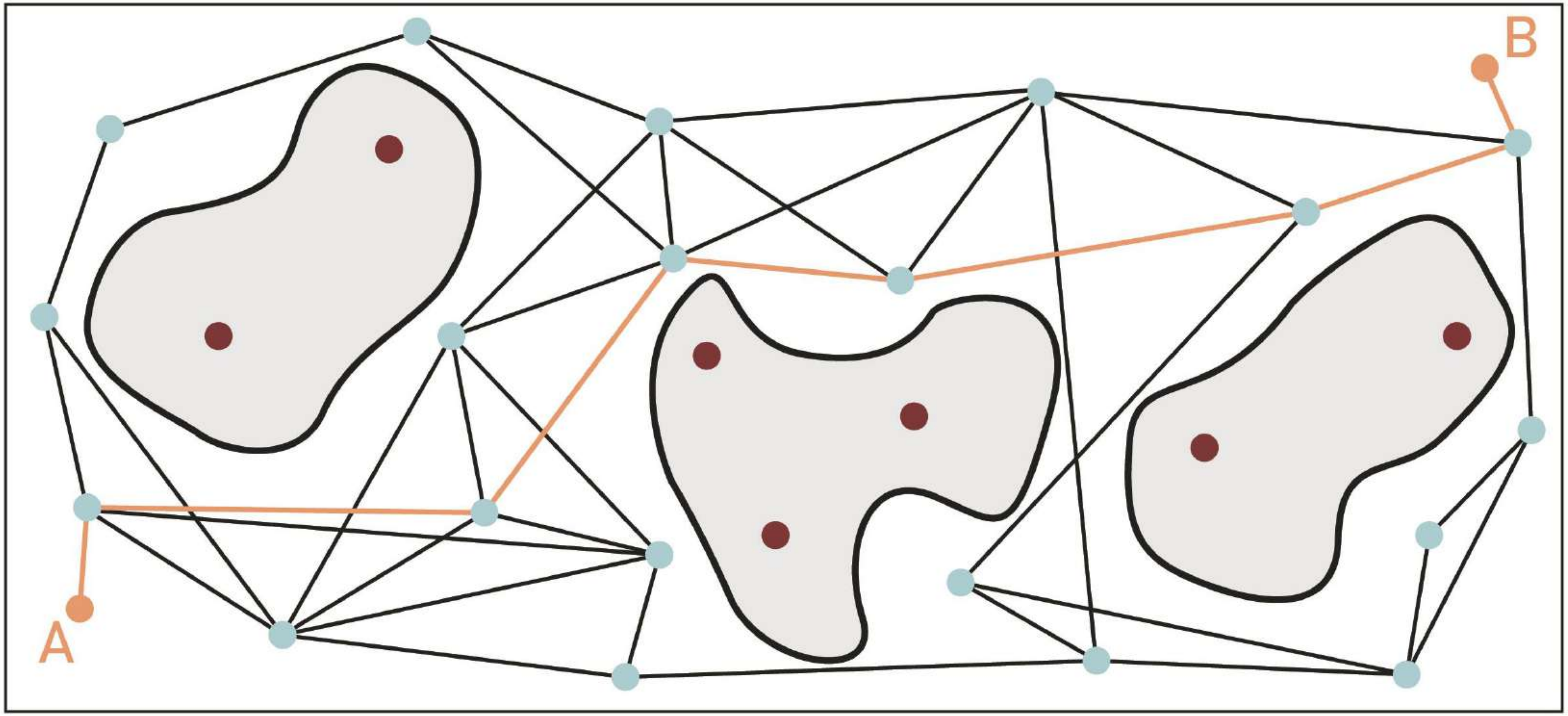
lvl 1: Simple Placing



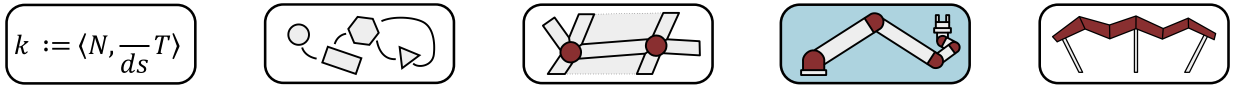
Movement: stationary & linear Sensing: sensorless Solving: interpolation Operation: pick & place



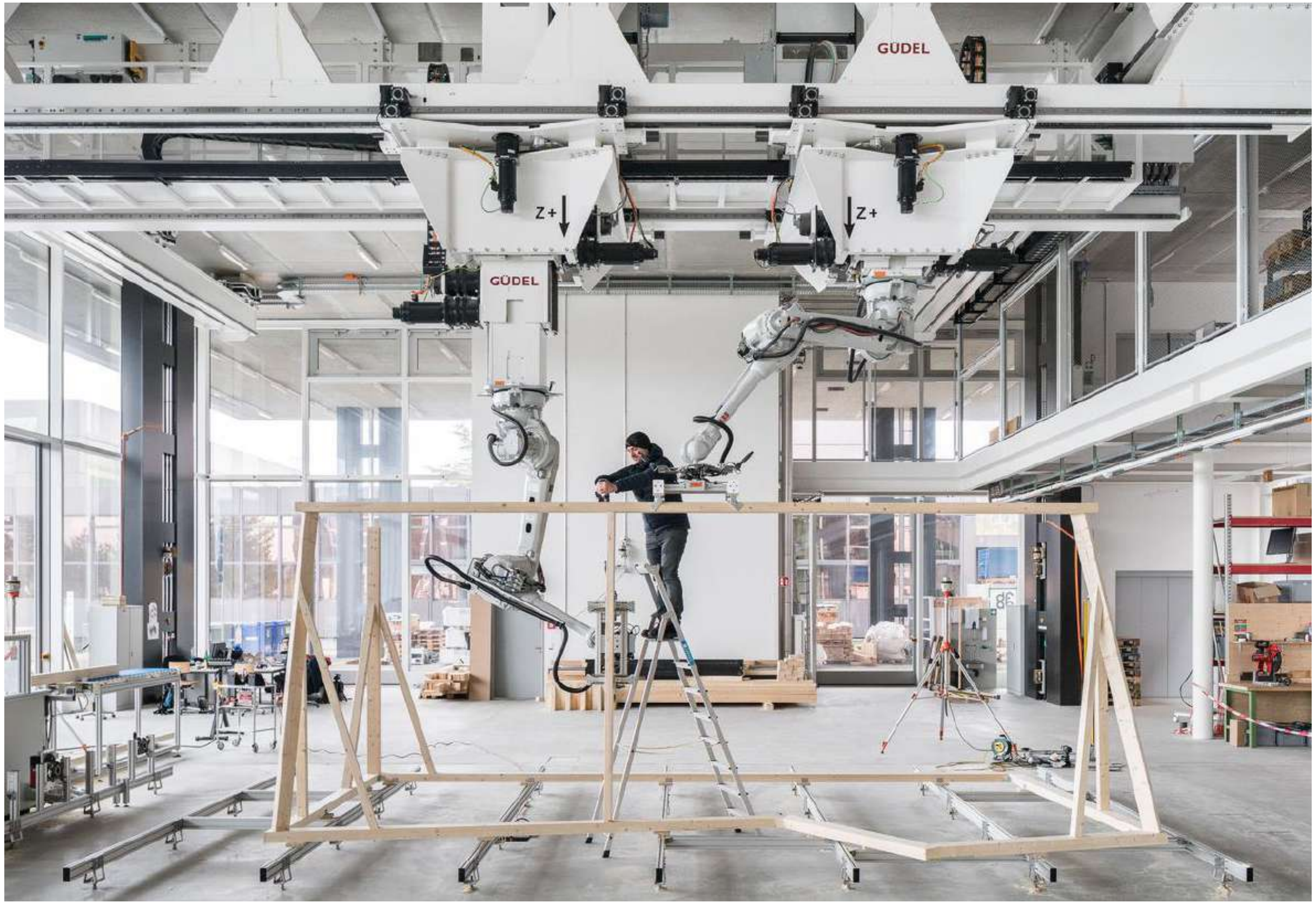
lvl 2: Complex Systems



Movement: XYZ gantry Sensing: force sensing Solving: collision free Operation: system building

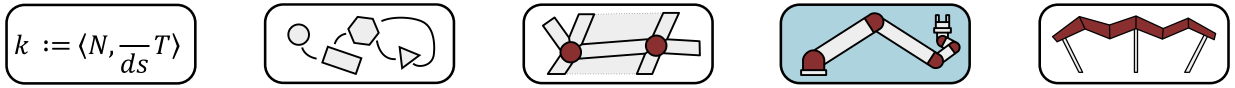


lvl 2: Complex Systems

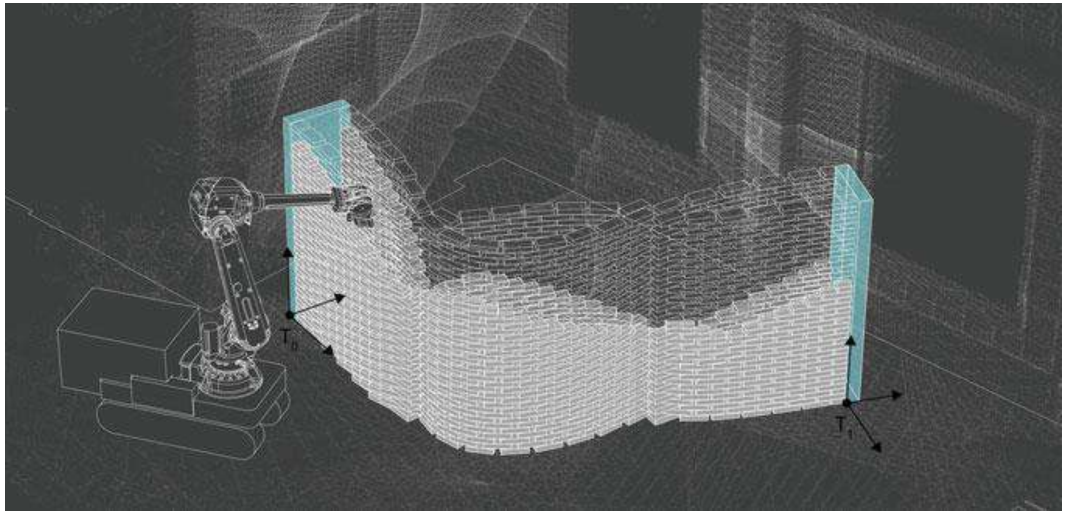


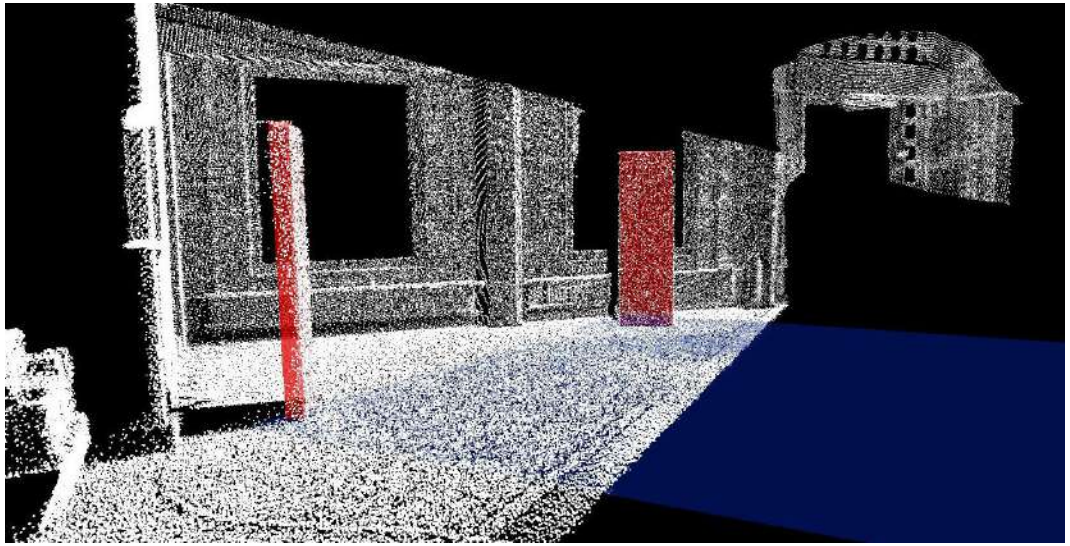
via ETH-Zurich

Movement: XYZ gantry   Sensing: force sensing   Solving: collision free   Operation: system building



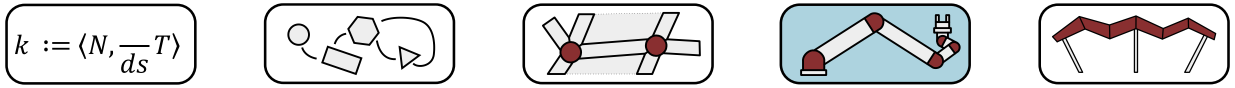
lvl 3: Smart Instructions



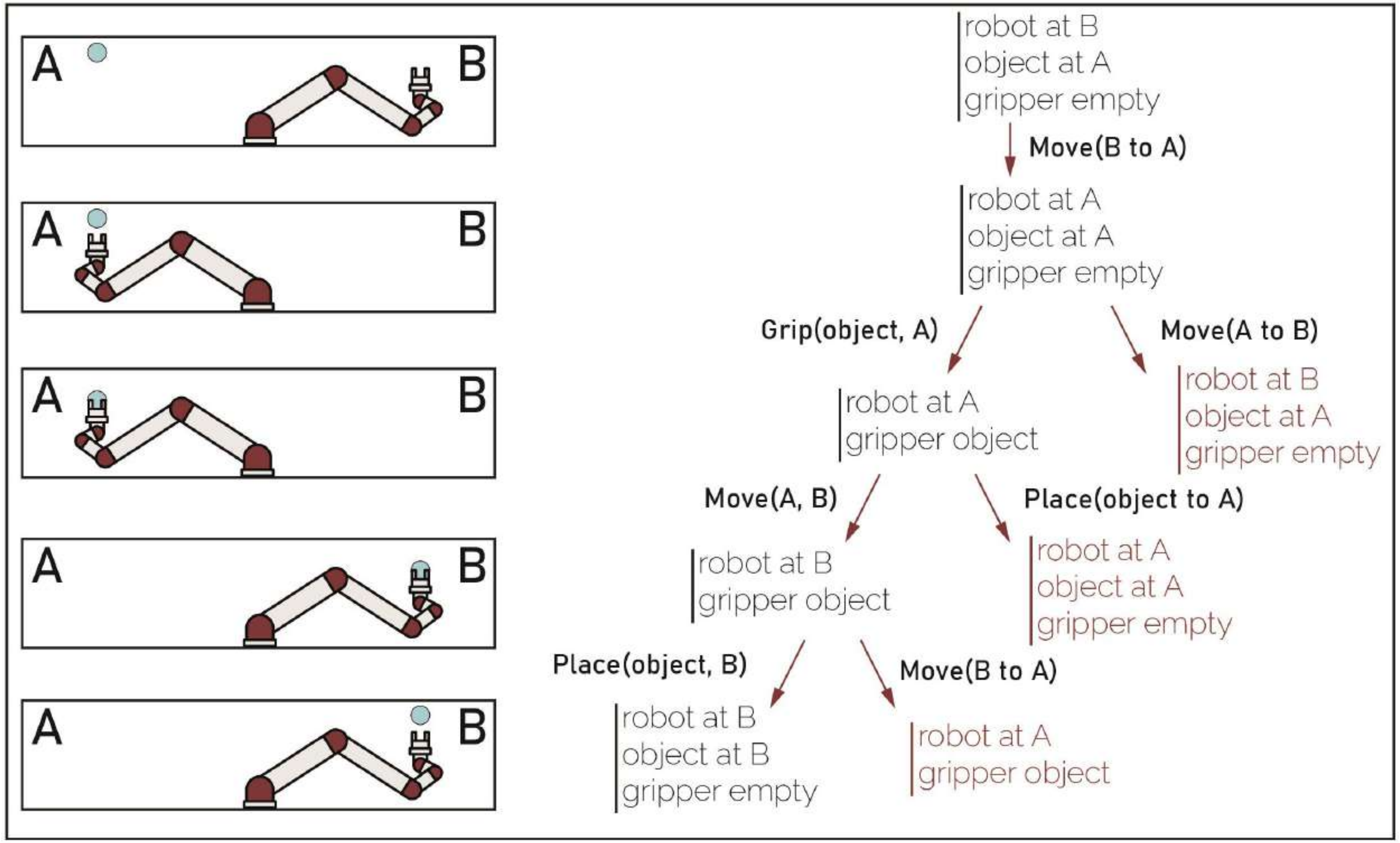


Dörfler K., et al. Mobile Robotic Brickwork, 2016.

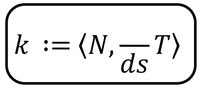
Movement: free Sensing: computer vision Solving: task planning Operation: symbolic instructions

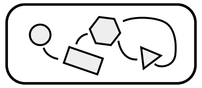


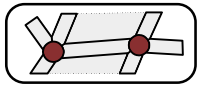
lvl 3: Smart Instructions

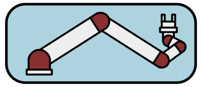


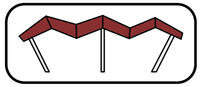
Movement: free   Sensing: computer vision   Solving: task planning   Operation: symbolic instructions



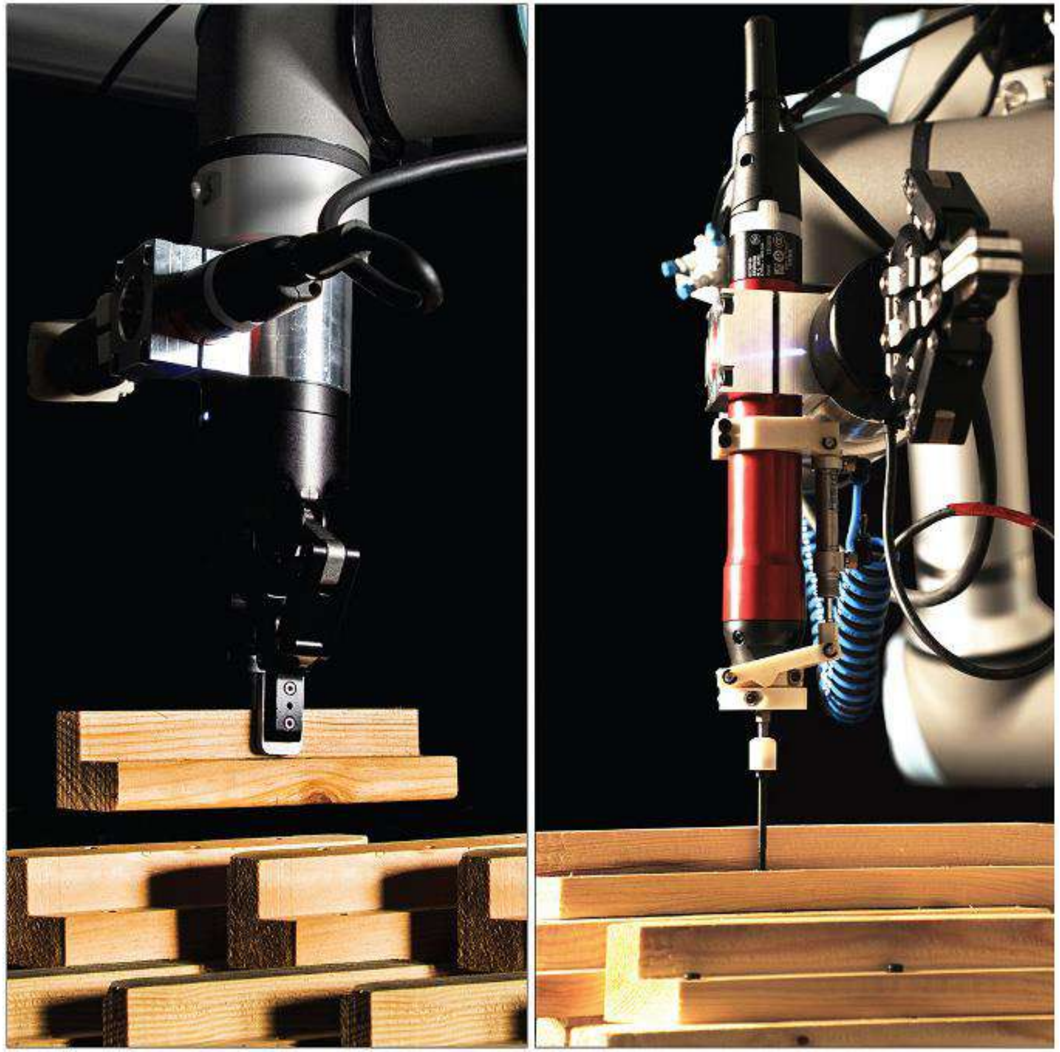








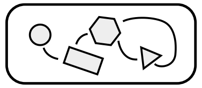
lvl 4: Diversified Agents

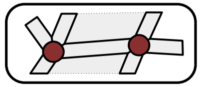


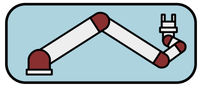
Kunic A., et al. Design and assembly automation of the Robotic Reversible Timber Beam, 2021.

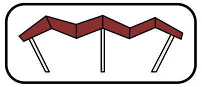
Movement: system integrated Sensing: swarm communication Solving: multi robot Operation: heterogeneous

$k := \langle N, \frac{d}{ds} T \rangle$









lvl 4: Diversified Agents

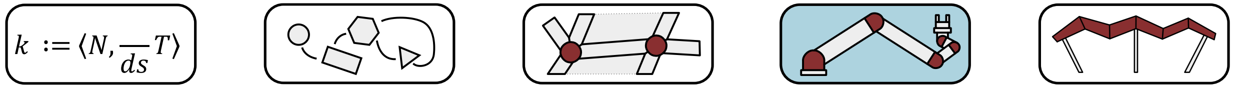
top left: Melenbrink N., et al. Towards force-aware robot collectives for on-site construction, 2017

top right: Delikanlı B., Gül F. L. A System for Truss Manipulation with Relative Robots: Designing and Prototyping HookBot, 2023.

bottom left: Leder S., et al. Leveraging Building Material as Part of the In-Plane Robotic Kinematic System for Collective Construction, 2022.

bottom right: Lochnicki G., et al. Co-Designing Material-Robot Construction Behaviors: Teaching distributed robotic systems to leverage active bending for light-touch assembly of bamboo bundle structures, 2021.

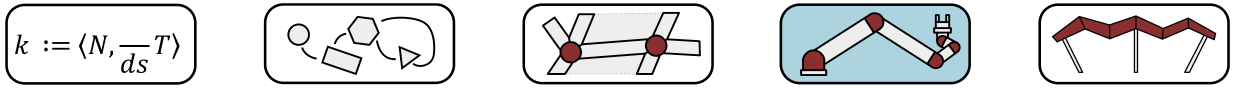
Movement: system integrated Sensing: swarm communication Solving: multi robot Operation: heterogeneous



System integrated robots that use swarm-like communication and heterogeneous multi-robot collaboration to achieve high-level task planning

Literature Review: Conclusion

theoretical model ⟷ practical model



Literature Review: Conclusion

	LVL 1: Simple Placing	LVL 2: Complex Systems	LVL 3: Smart Instructions	LVL 4: Diversified Agents
Movement	stationary & linear	XYZ Gantry	free	system integrated
Sensing	sensorless	force limiting	computer vision	swarm communication
Solving	interpolation	collision free	task planning	multi robot
Operation	pick & place	system building	symbolic instructions	heterogeneous

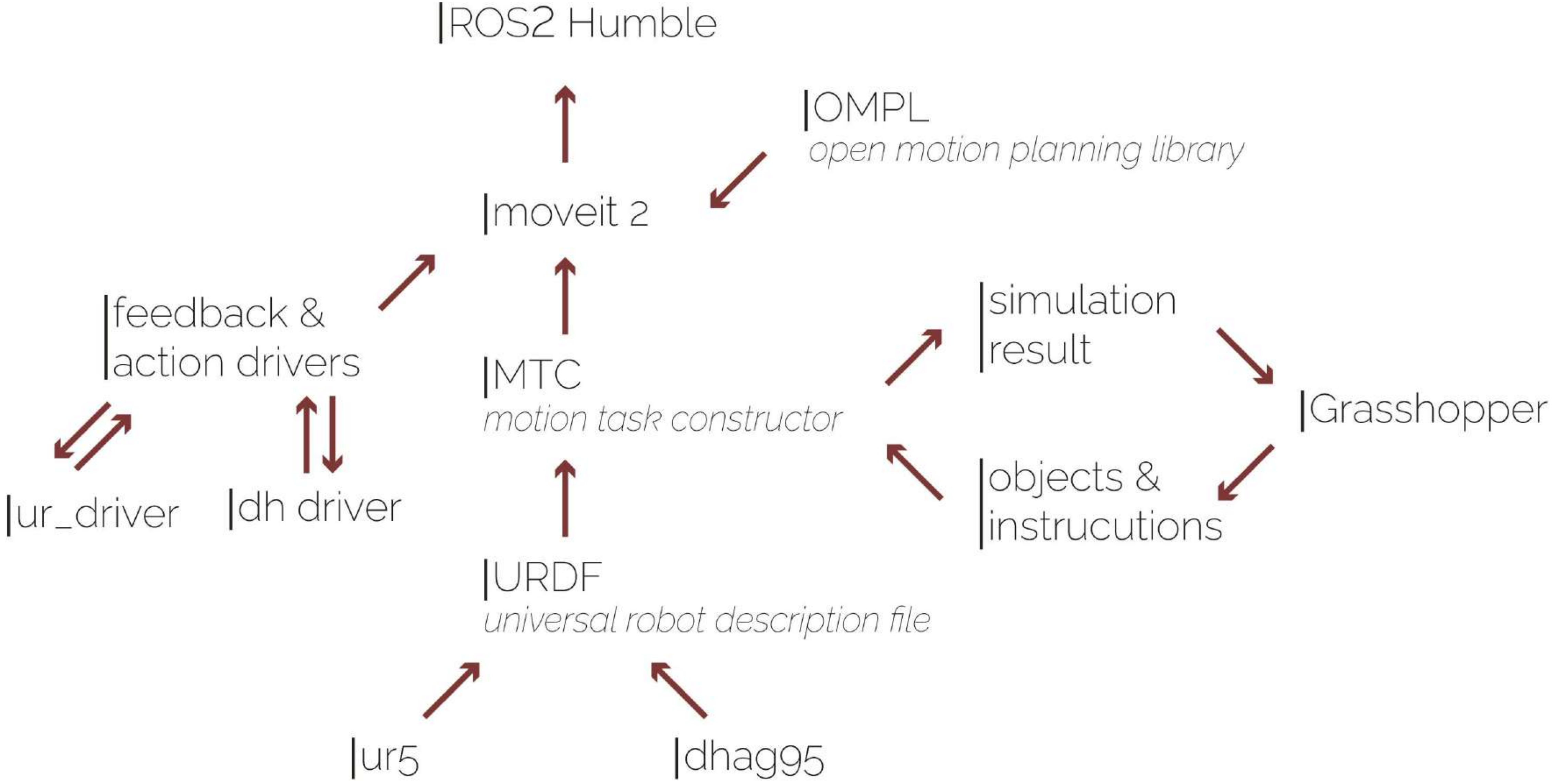
ROS & MoveIt

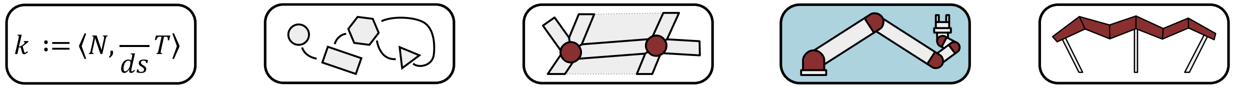
Via: moveit.ros.org

Open Source (BSD)
Free
Widely used
Community support
Documentation
Technologically advanced

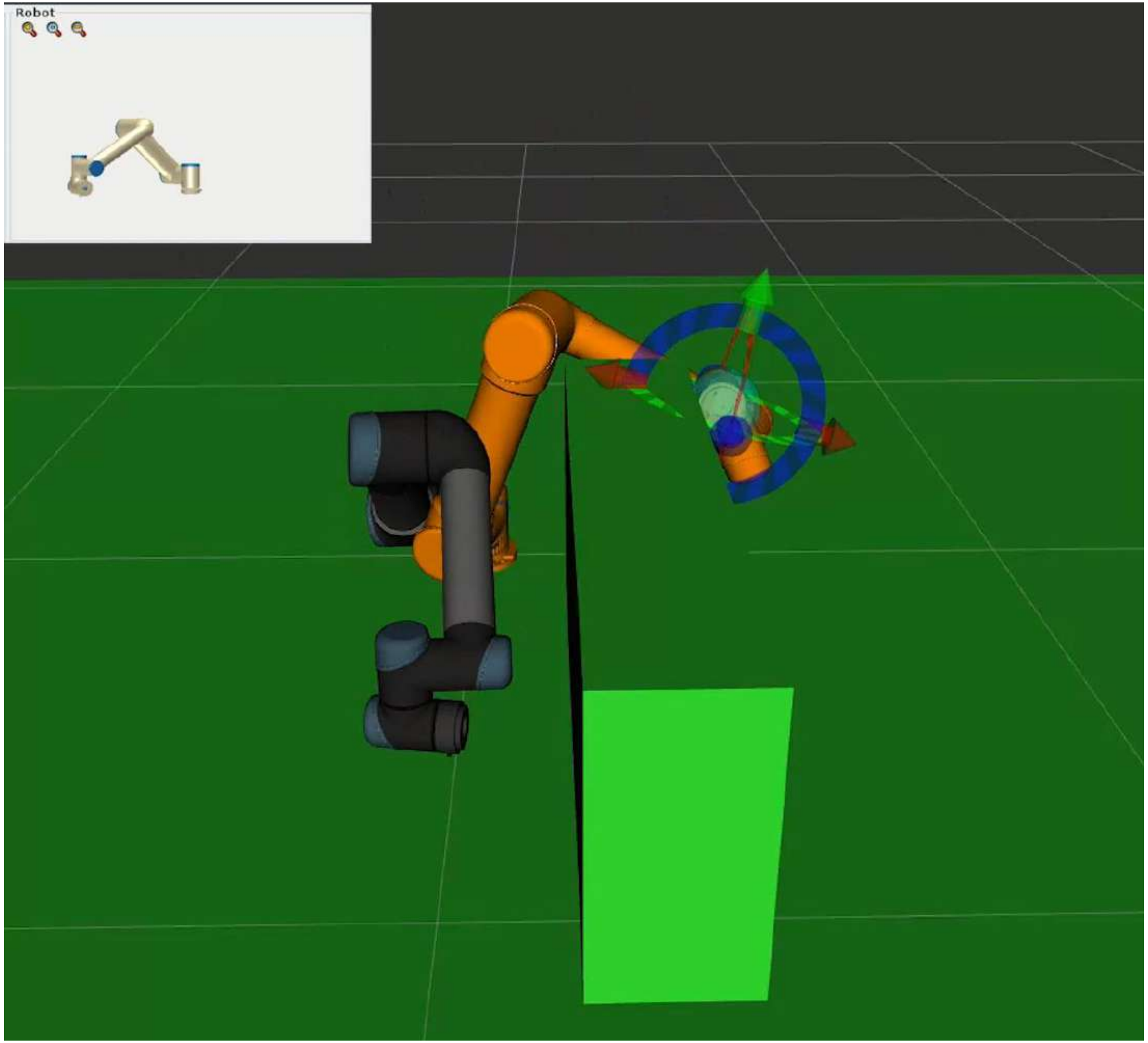
Linux based
Complex system architecture
Low level (C++)
Actively in development

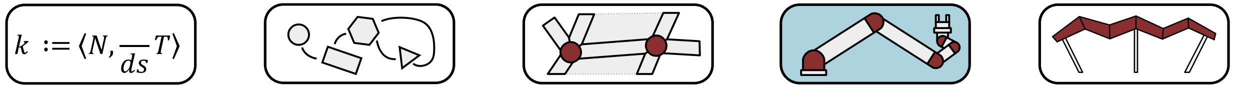
ROS & MoveIt


ROS2 Humble
OMPL
open motion planning library
moveit 2
feedback &
action drivers
MTC
motion task constructor
simulation
result
Grasshopper
objects &
instrucutions
ur_driver
dh driver
URDF
universal robot description file
ur5
dhag95

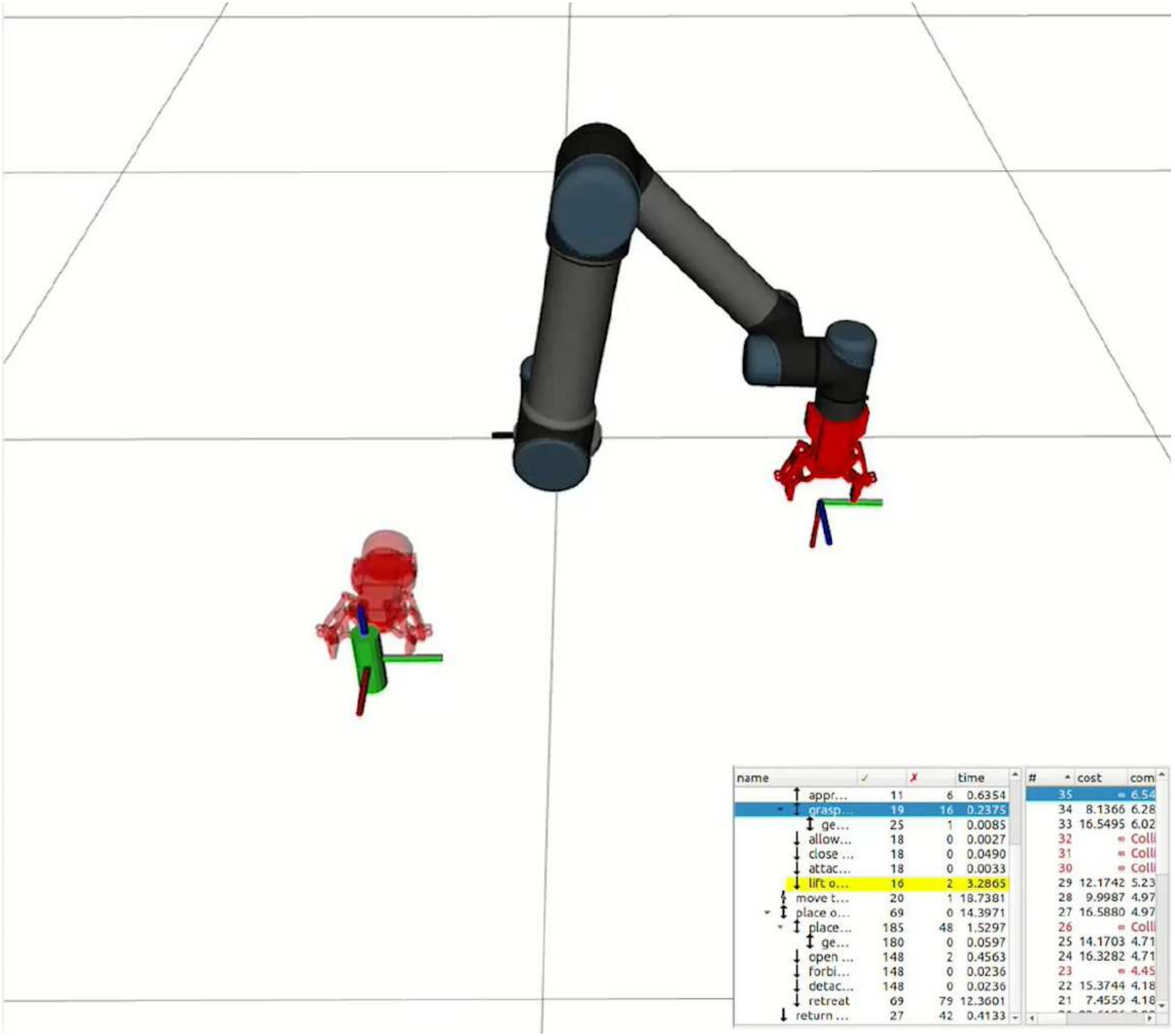


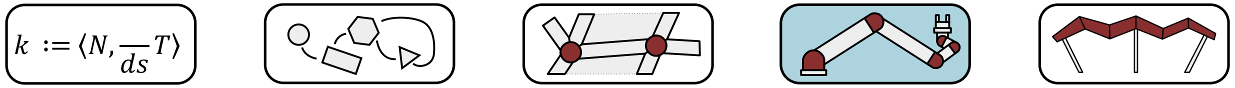
ROS & MoveIt



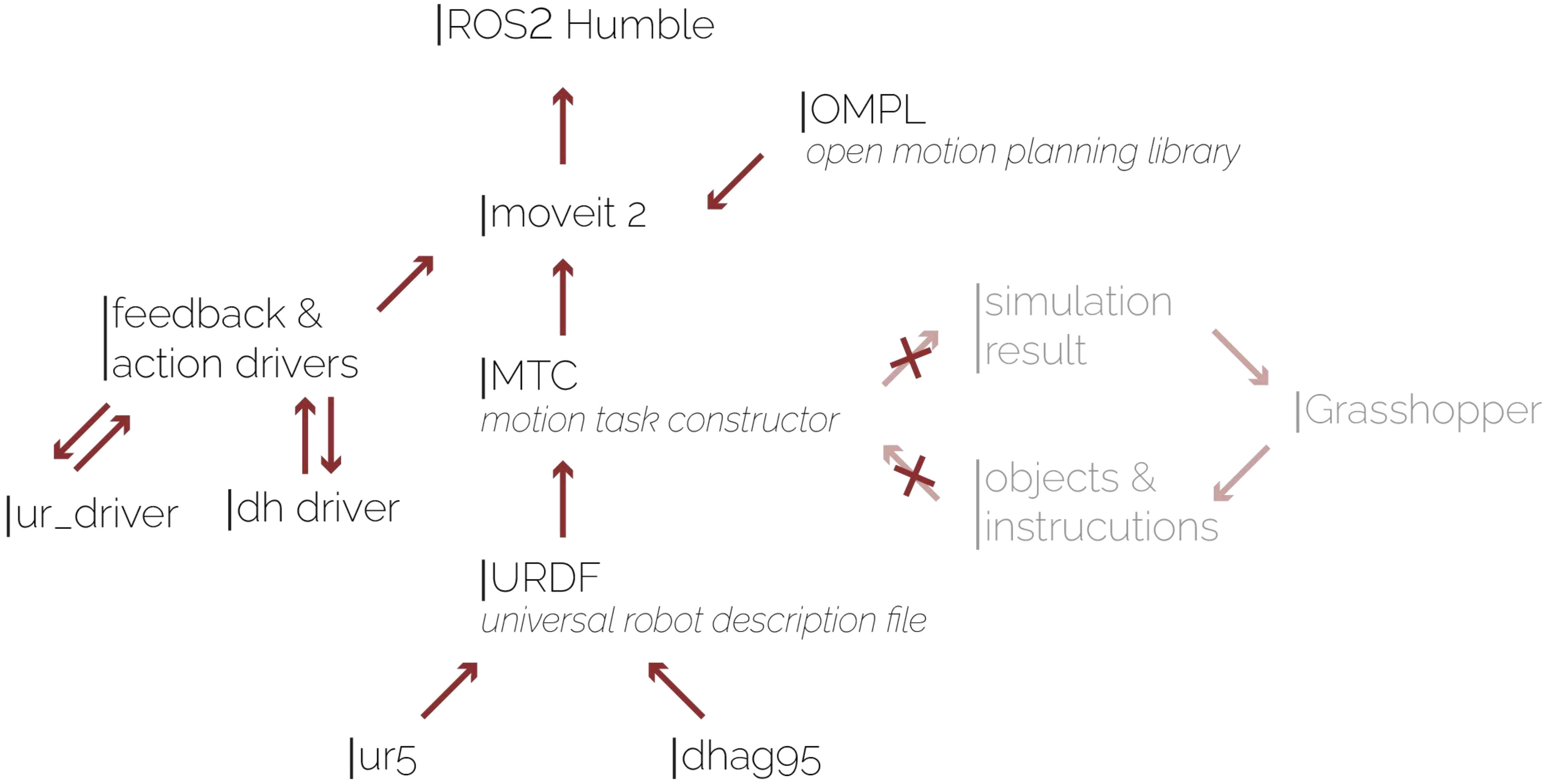


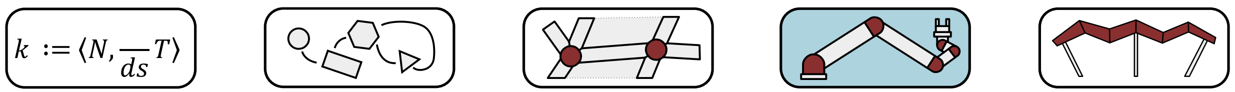
ROS & MoveIt


name ✓ ✗ time
appr… 11 6 0.6354
grasp… 19 16 0.2375
ge… 25 1 0.0085
allow… 18 0 0.0027
close … 18 0 0.0490
attac… 18 0 0.0033
lift o… 16 2 3.2865
move t… 20 1 18.7381
place o… 69 0 14.3971
place… 185 48 1.5297
ge… 180 0 0.0597
open … 148 2 0.4563
forbi… 148 0 0.0236
detac… 148 0 0.0236
retreat 69 79 12.3601
return … 27 42 0.4133
cost com
35 ∞ 6.54
34 8.1366 6.28
33 16.5495 6.02
32 ∞ Colli
31 ∞ Colli
30 ∞ Colli
29 12.1742 5.23
28 9.9987 4.97
27 16.5880 4.97
26 ∞ Colli
25 14.1703 4.71
24 16.3282 4.71
23 ∞ 4.45
22 15.3744 4.18
21 7.4559 4.18



ROS & MoveIt


ROS2 Humble
OMPL
open motion planning library
moveit 2
feedback &
action drivers
MTC
motion task constructor
simulation
result
Grasshopper
objects &
instructions
ur_driver
dh driver
URDF
universal robot description file
ur5
dhag95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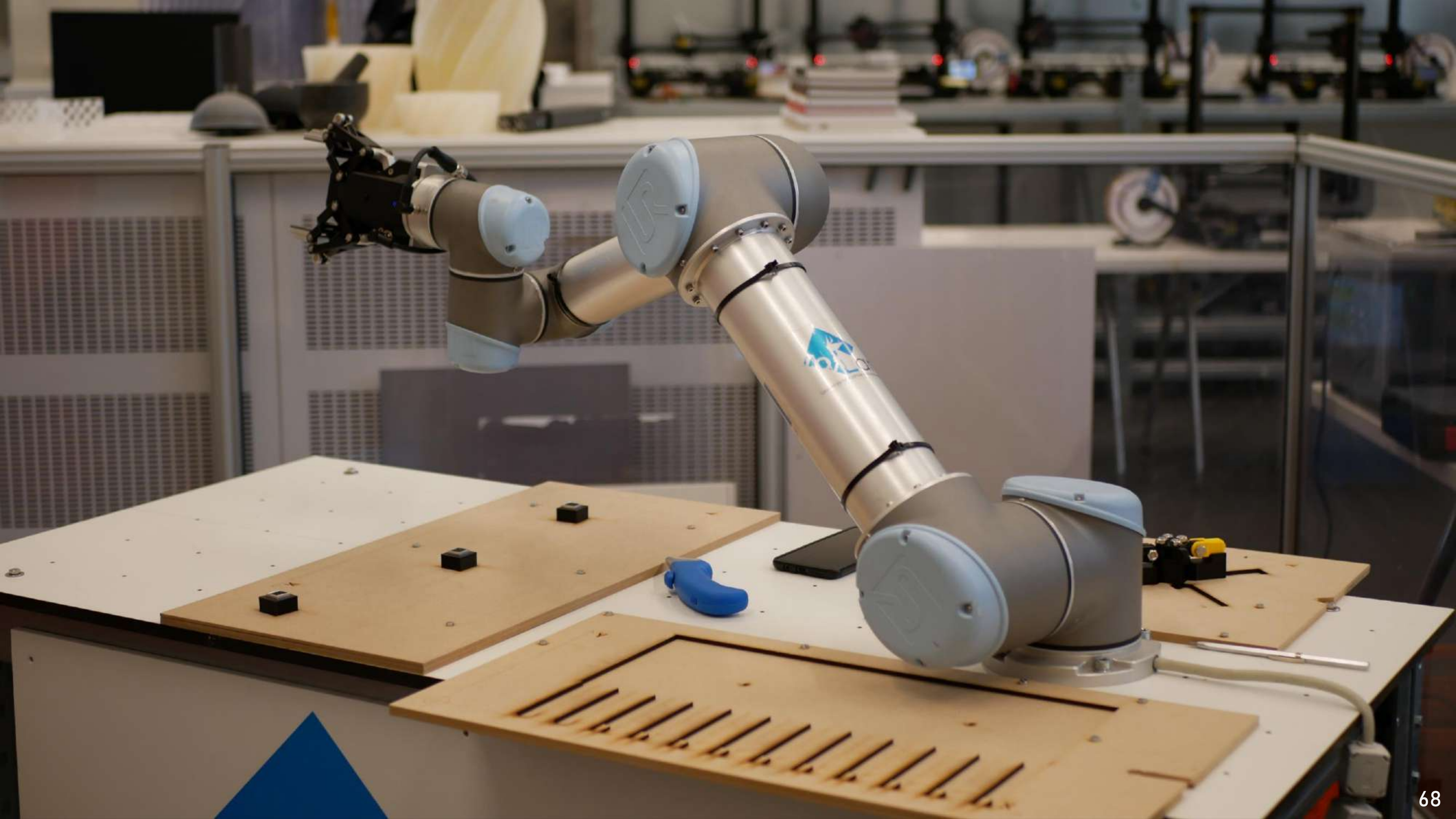
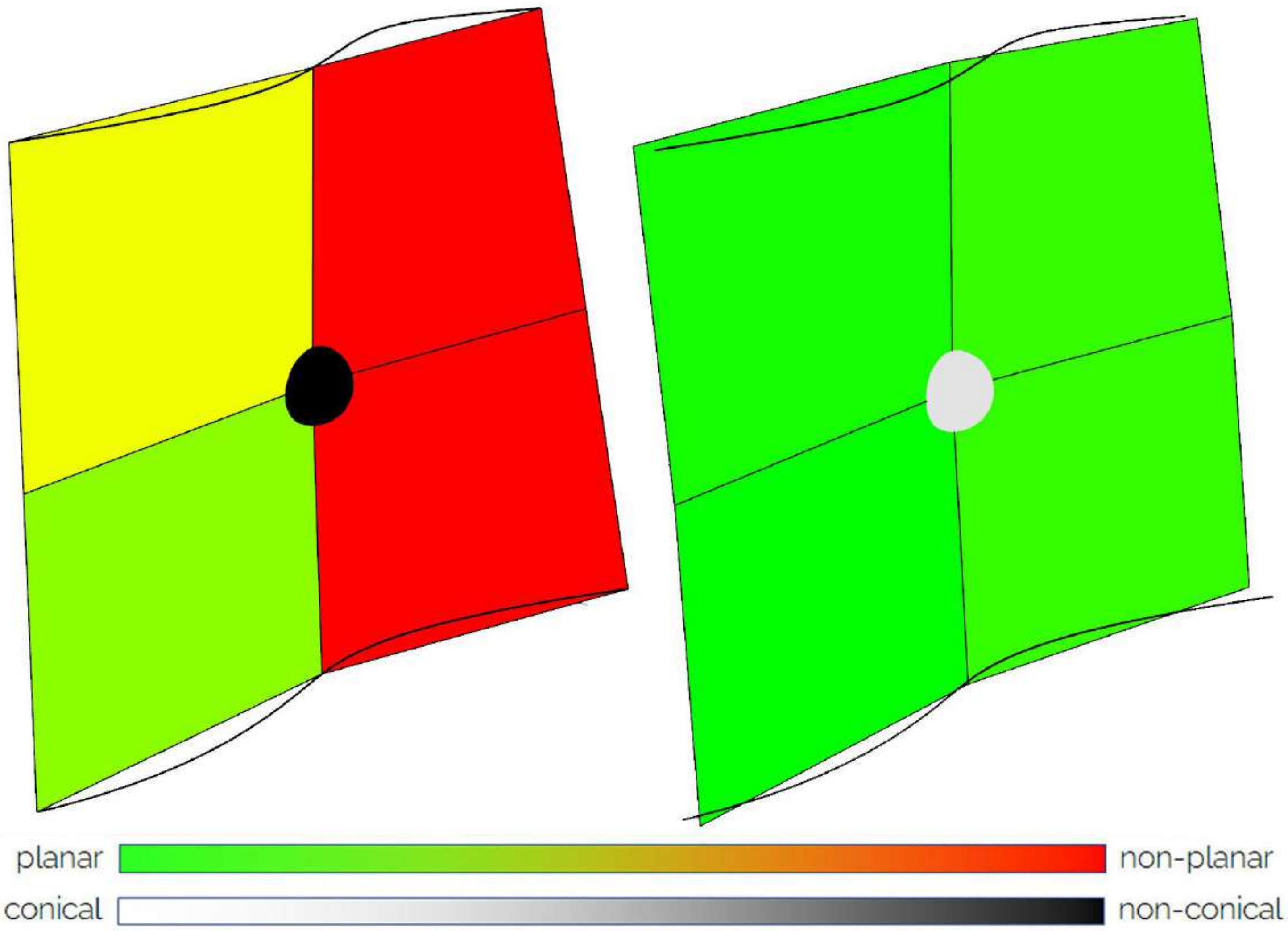
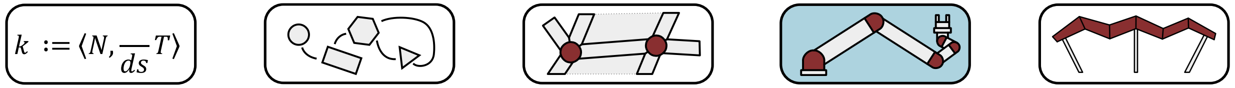
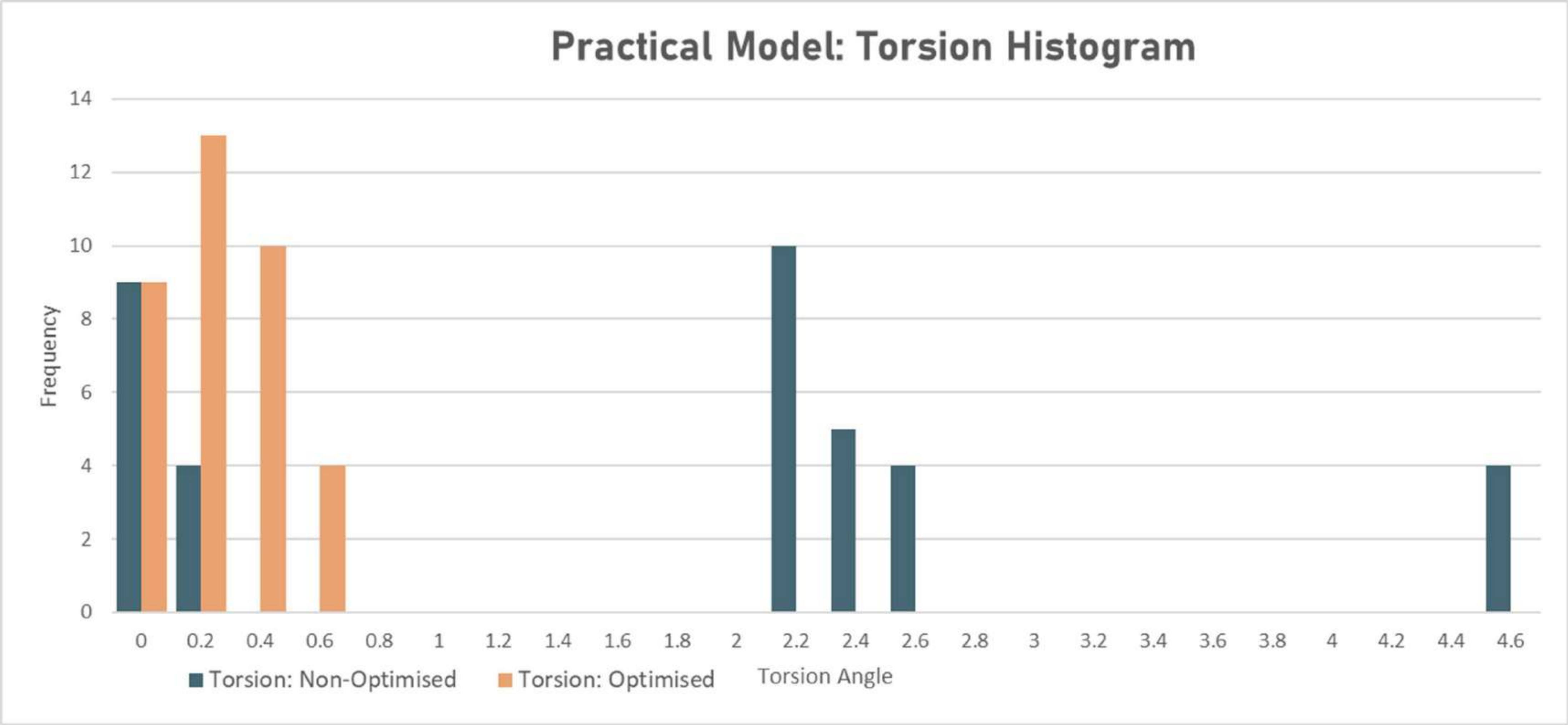


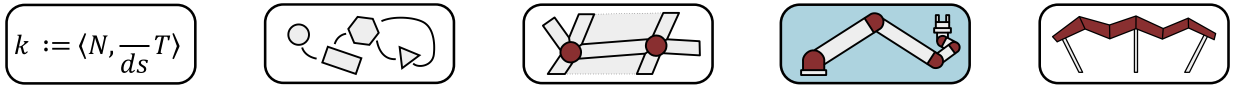
Practical assembly – shape



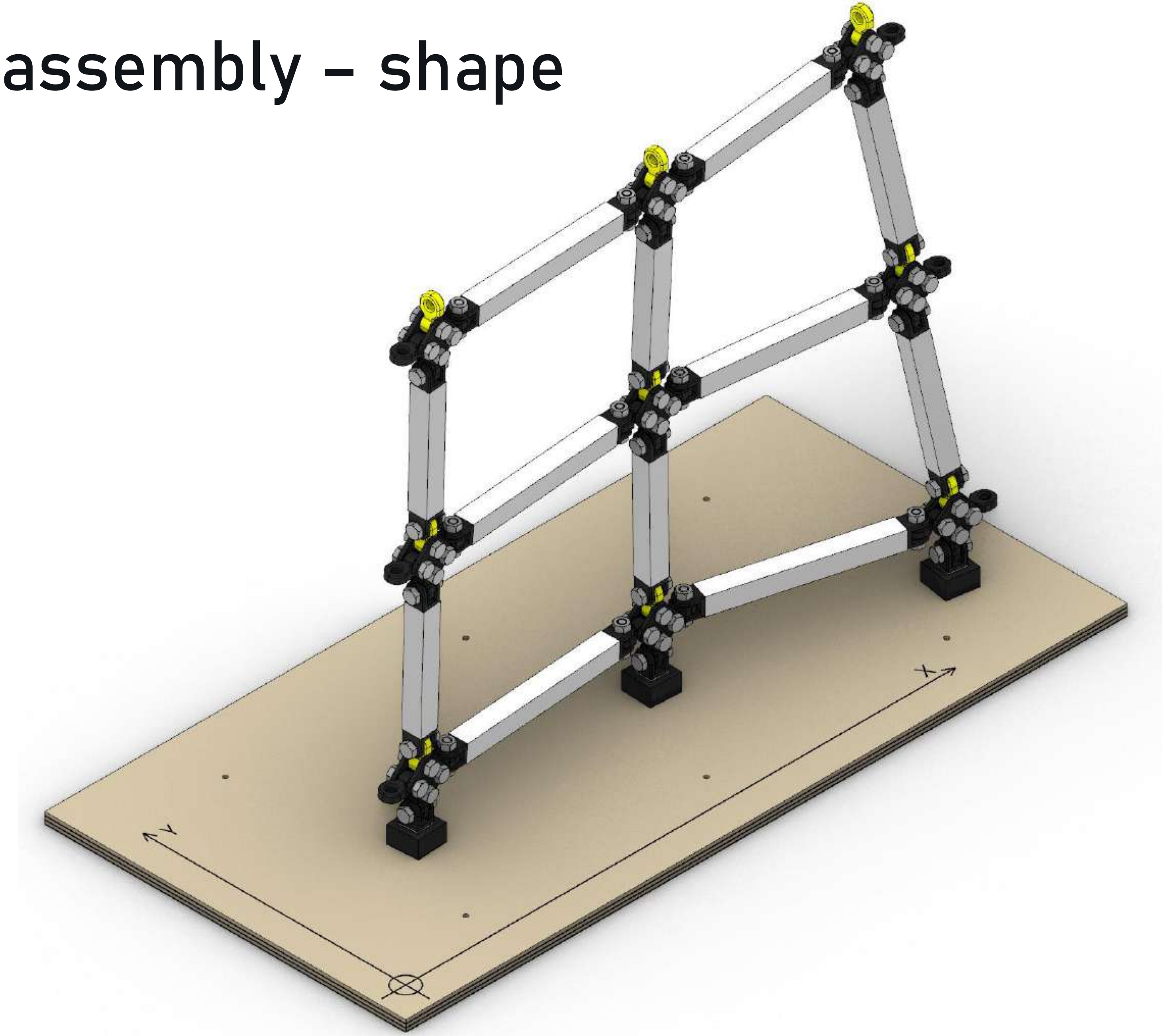


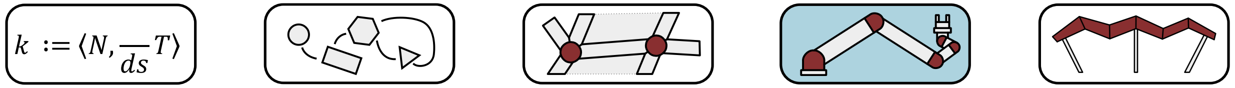
Practical assembly – shape



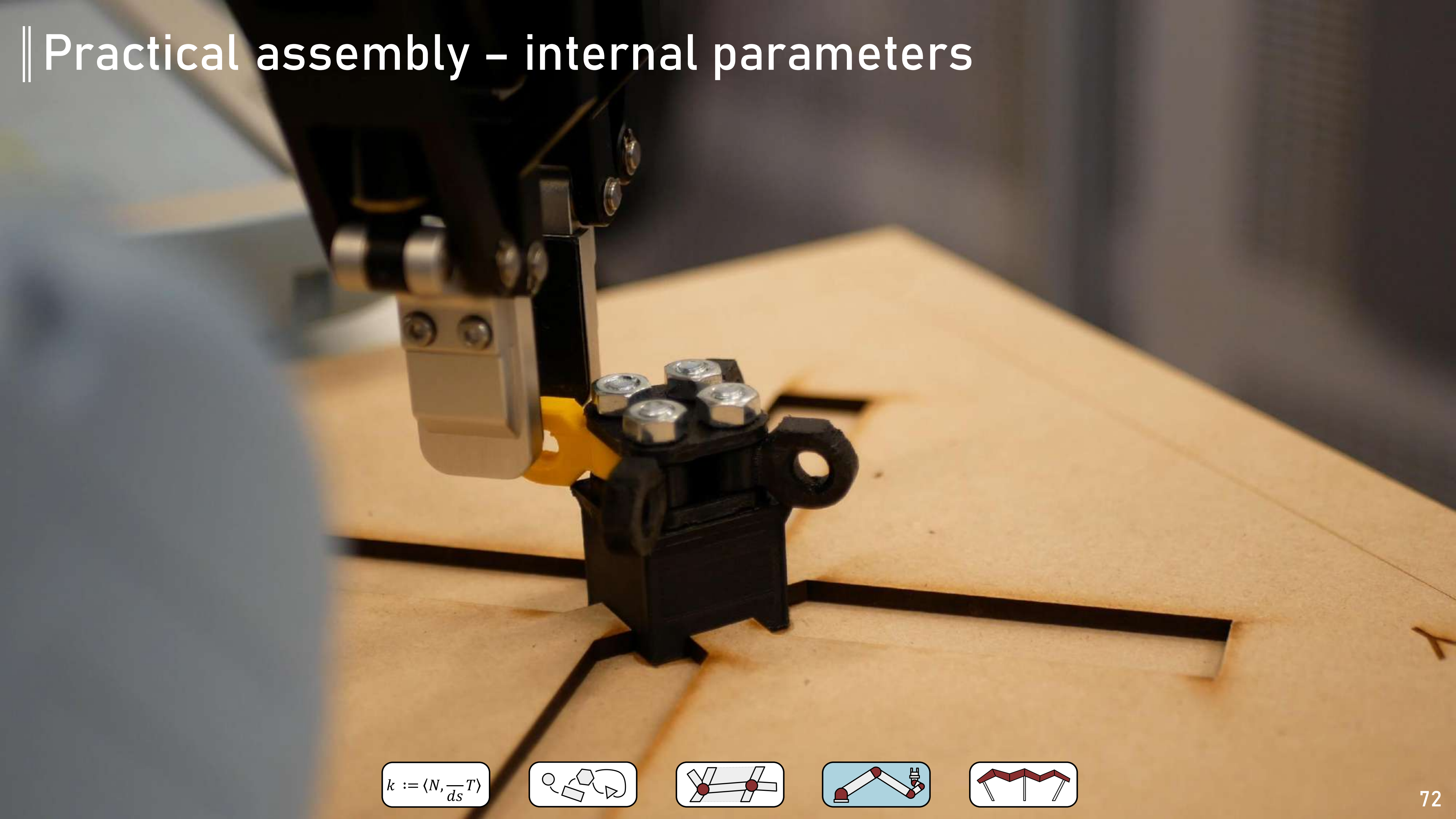


Practical assembly – shape

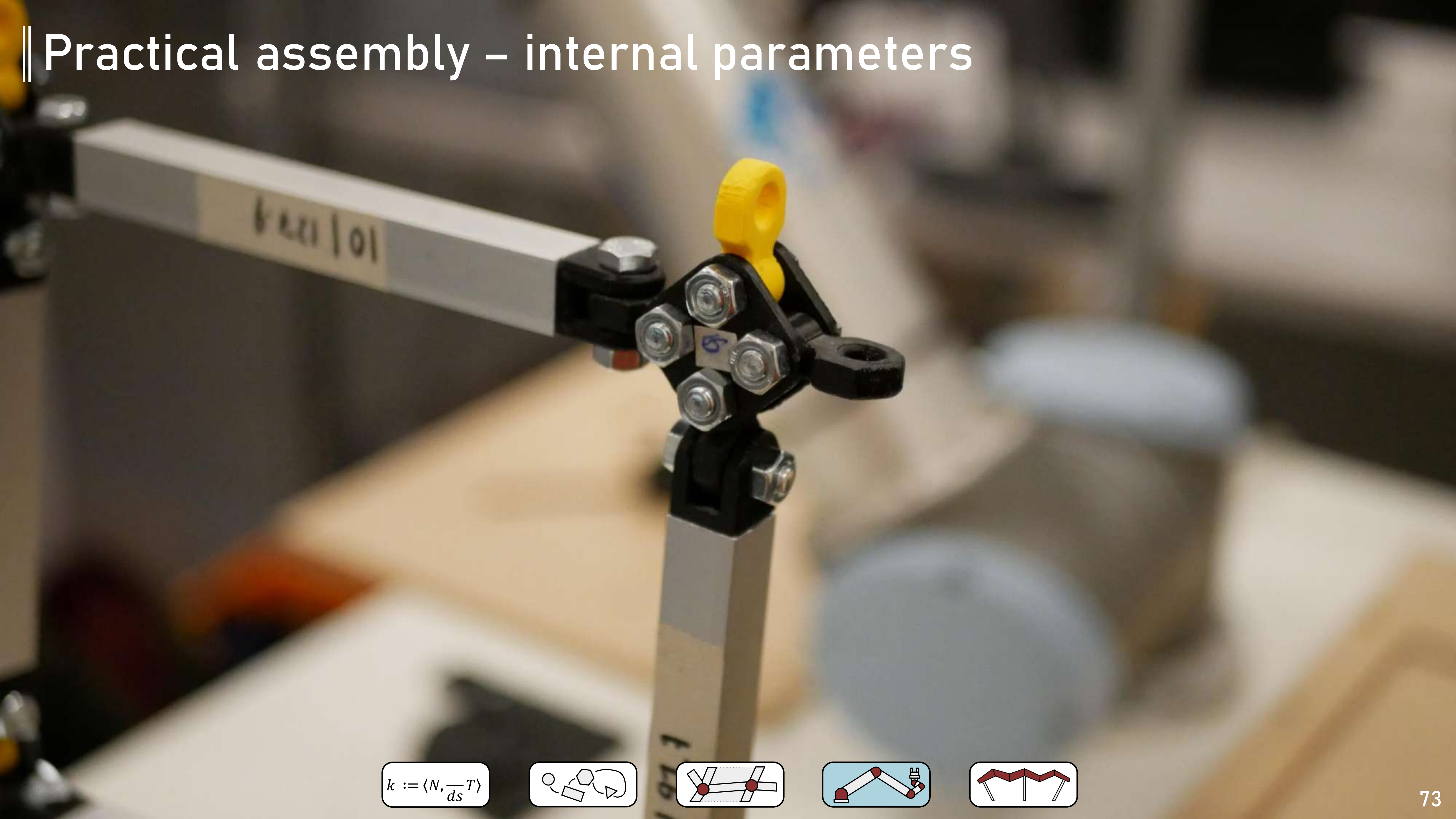




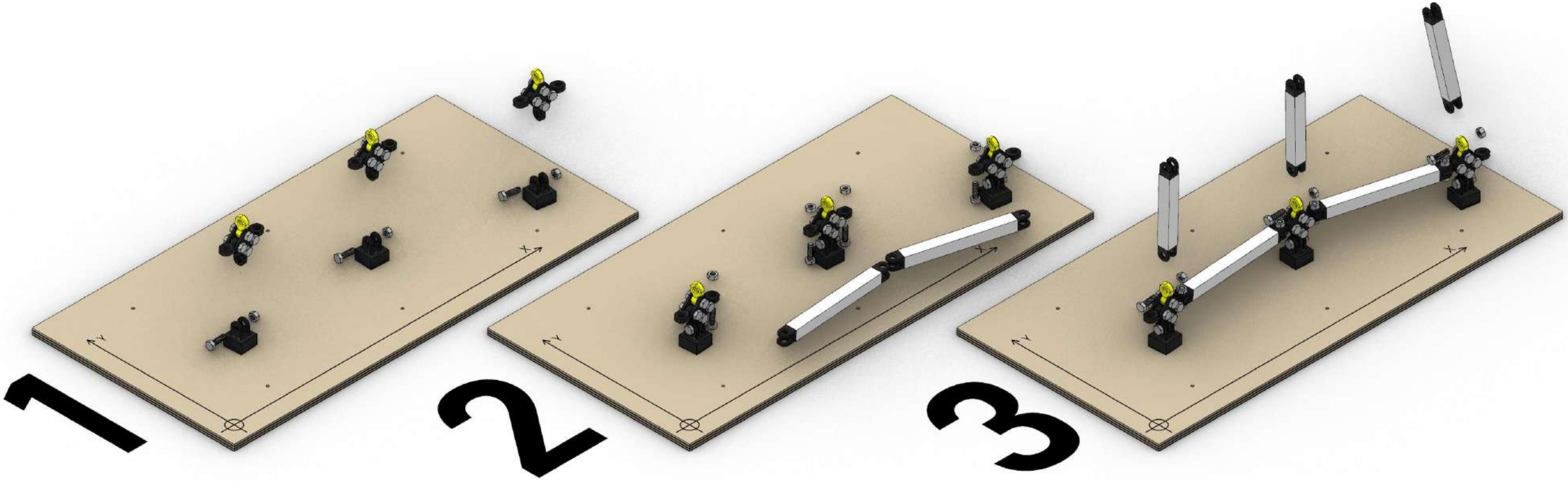
Practical assembly – internal parameters

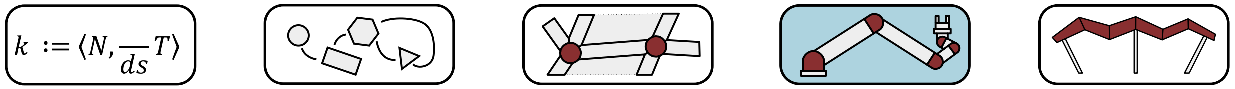


Practical assembly – internal parameters

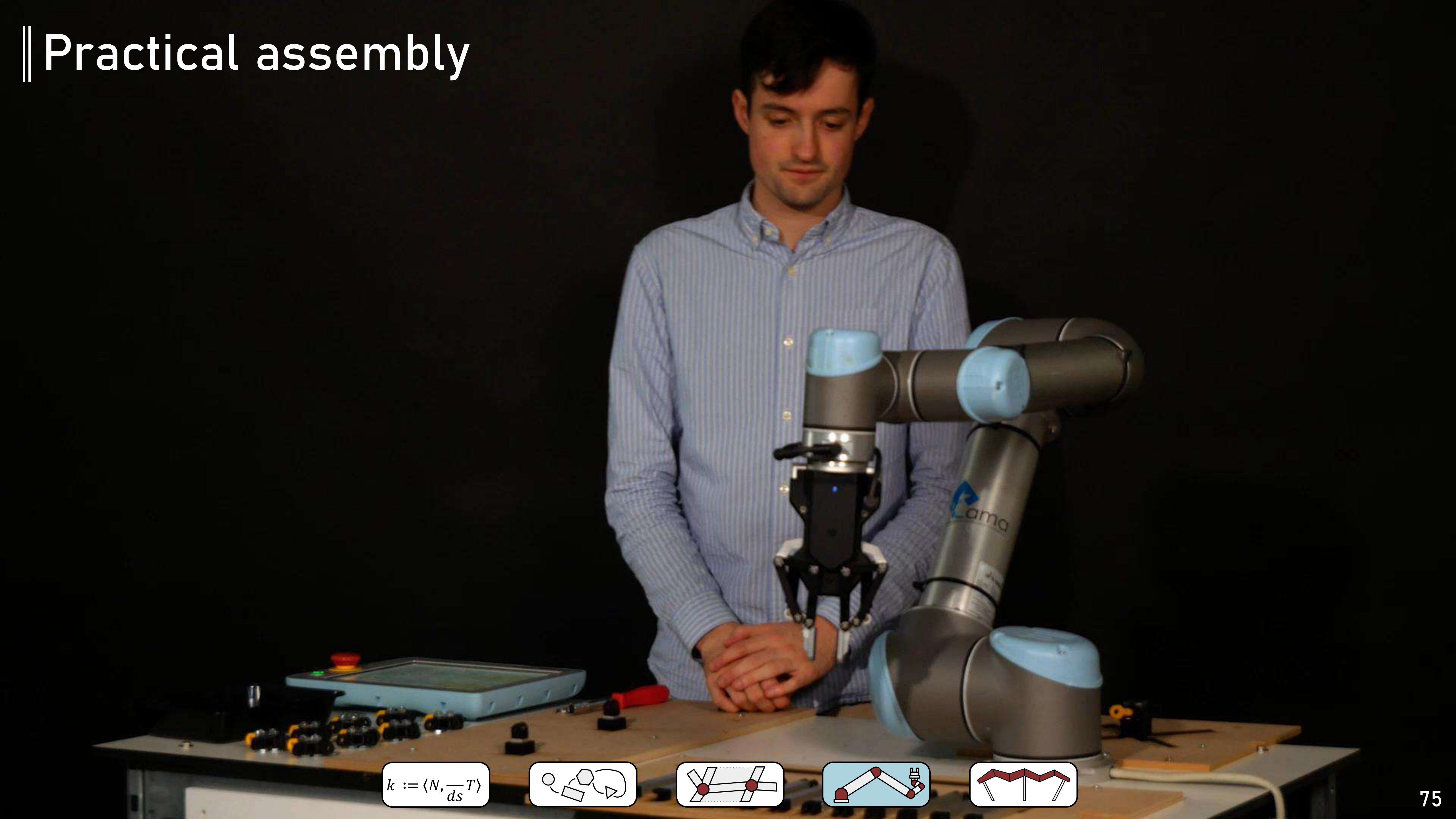


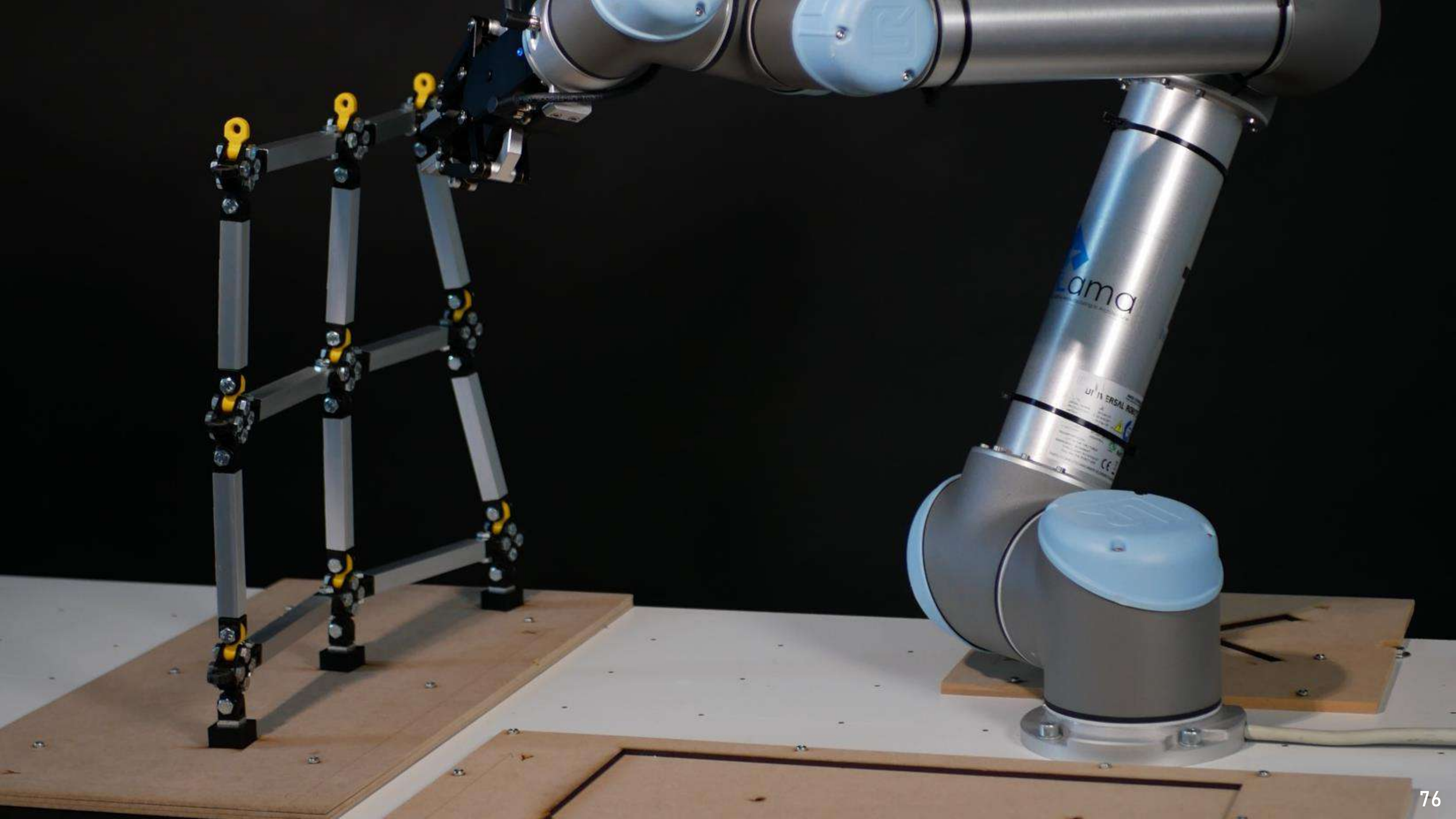
Practical assembly – build order



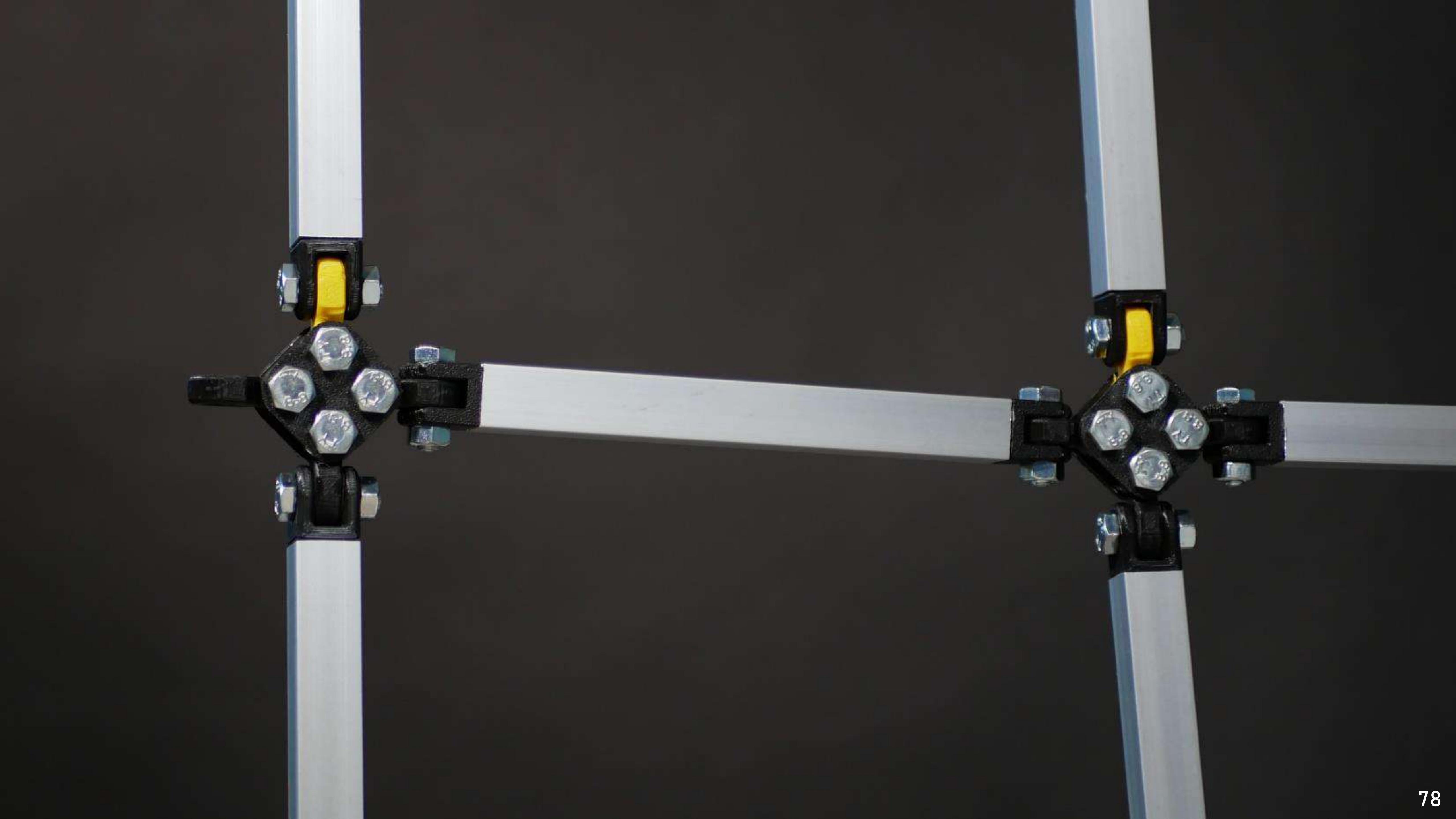


Practical assembly





During the assembly process it was found that not compensating for torsion likely resulted in internal stresses and a less accurate geometry



7 Pavilion Construction

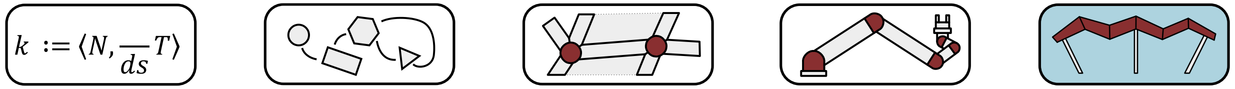
How can the designed nodes & beams be used in a computationally informed robotic construction process to automatically assemble full scale architecture?

Pavilions often will not consider the direct functionality of the architecture, providing freedom to develop specific technologies

Pavilion research - materials

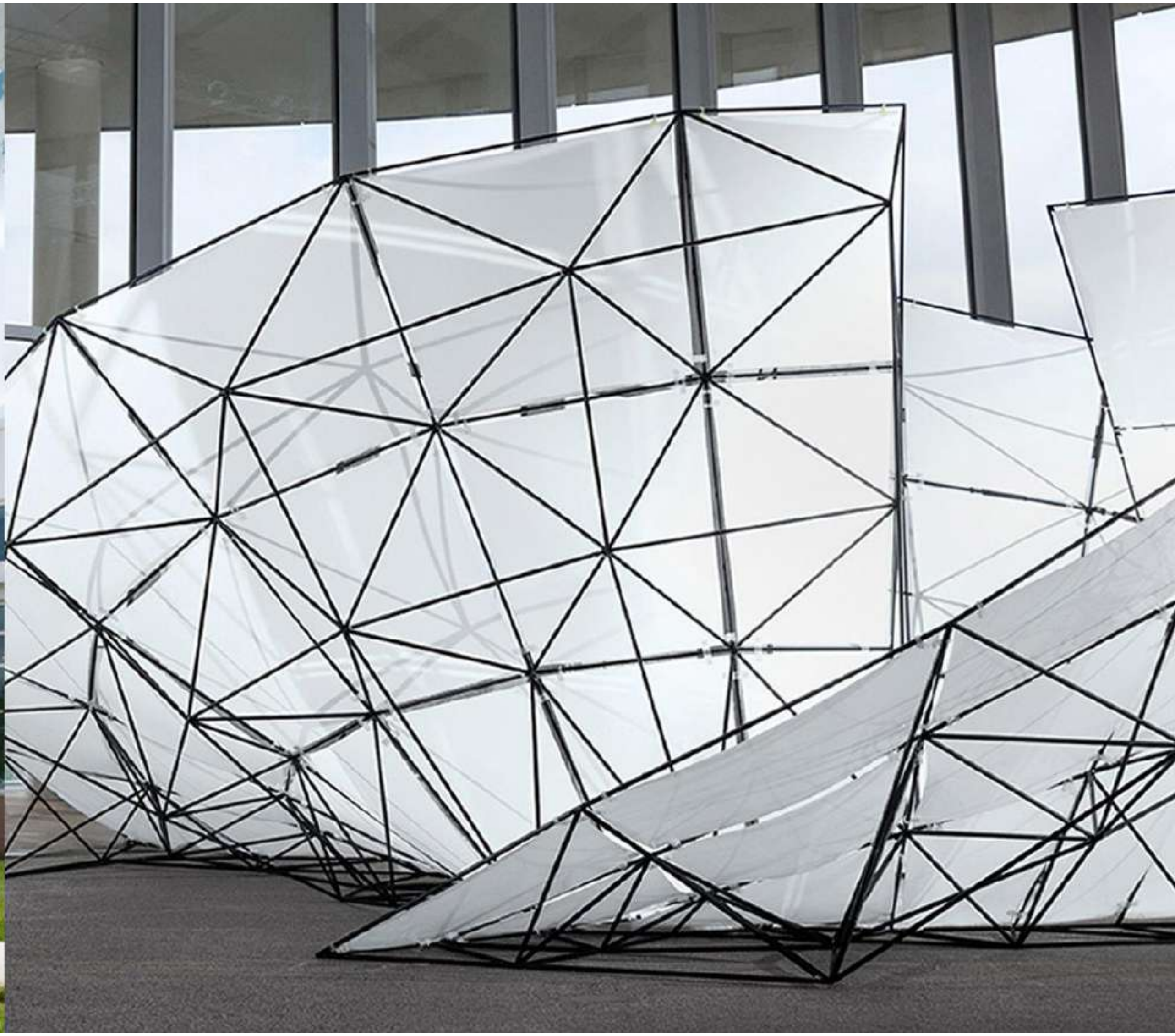
Debney P., et al. Advanced Applications in Computational Design. 2022

VTN Architects. Bamboo Stalactite. 2018.

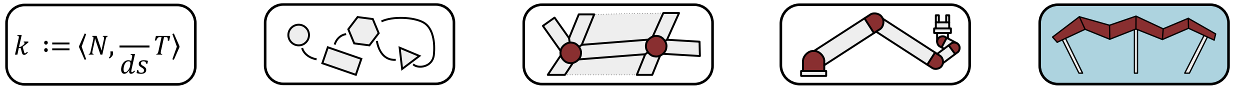


Pavilion research - systems

theverymany. Pillars of Dreams. 2019.



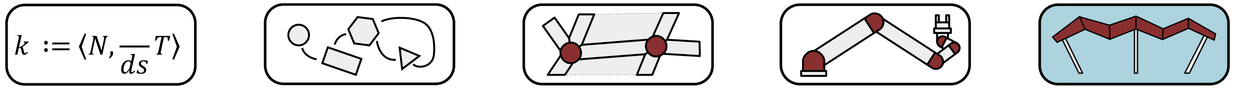
Formlabs. 3D Printing at Scale: The FUSE Pavilion. 2017



Pavilion research - robotics

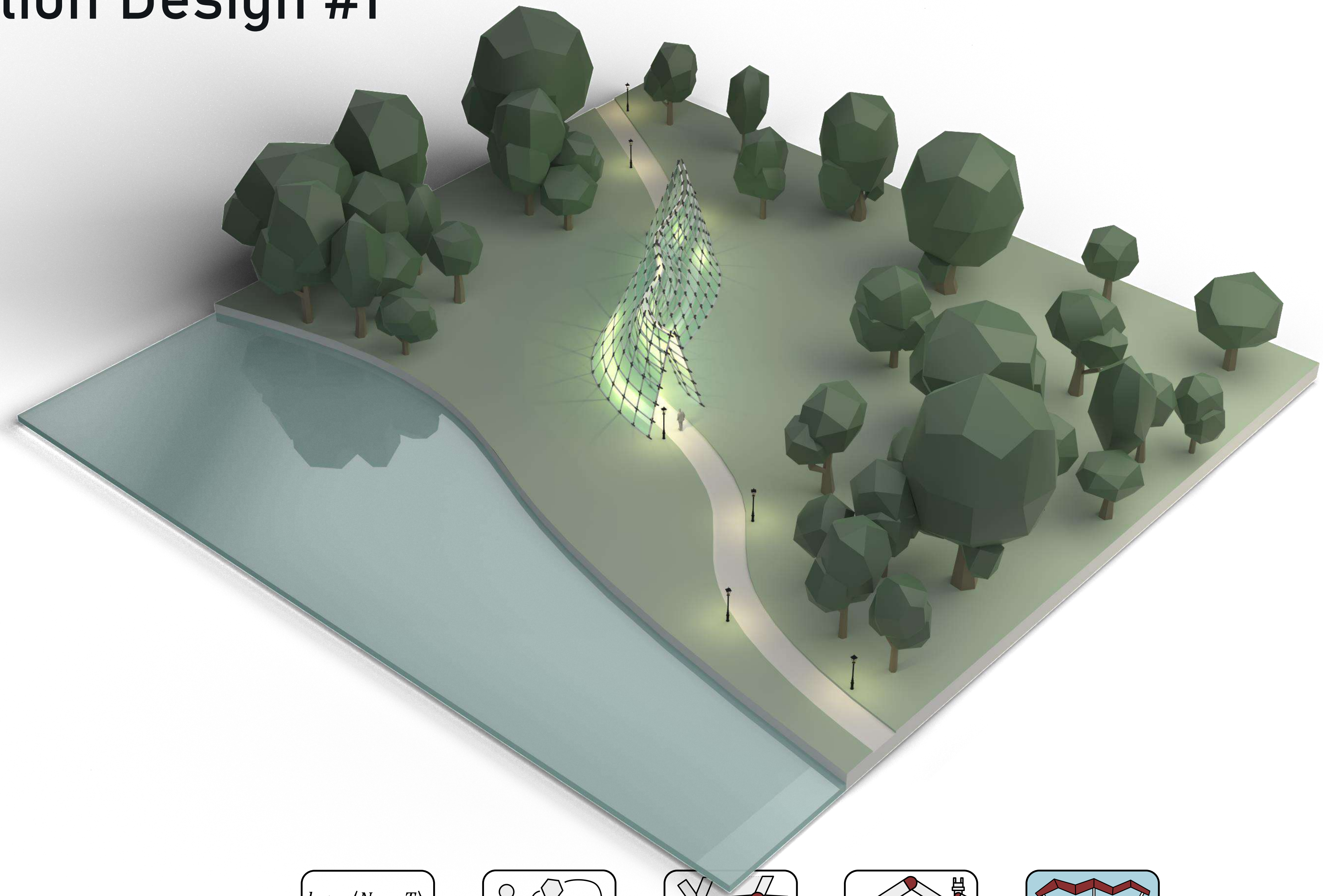
Frearson A. Robotically Fabricated Structure. 2022.

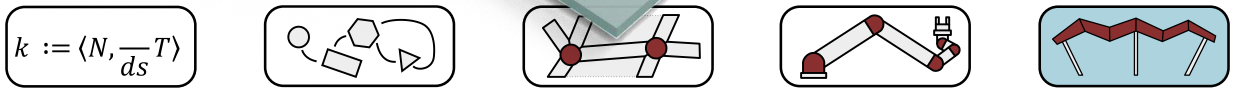
Knippers J. ICD/ITKE Research Pavilion 2012: Coreless Filament Winding Based on the Morphological Principles of an Arthropod Exoskeleton". 2015.



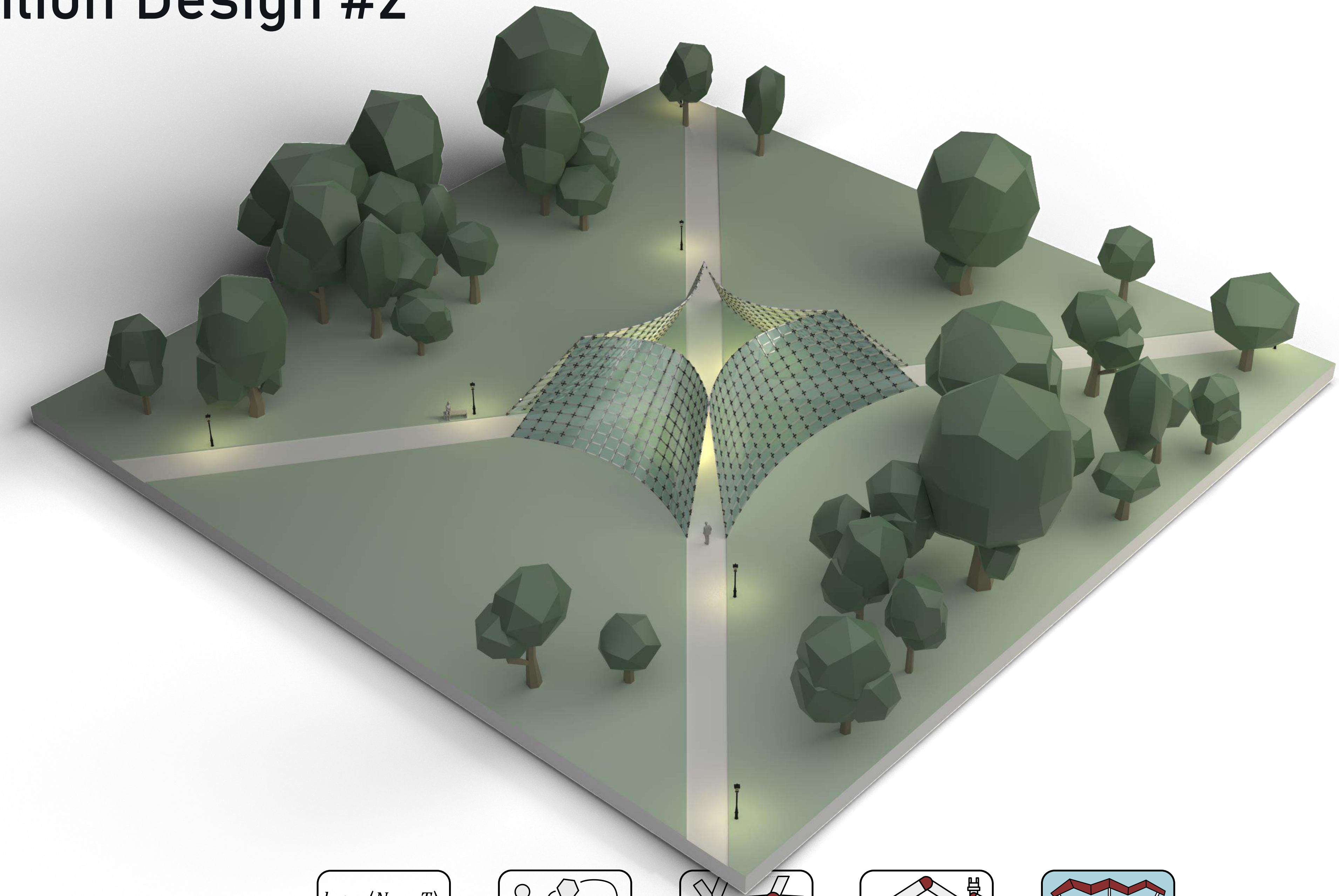
A reusable node and beam system combined with robotic construction can enable a revolutionary change from rigid to fluid architecture where form and function can adapt over time

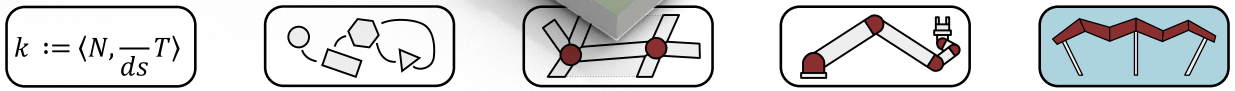
Pavilion Design #1



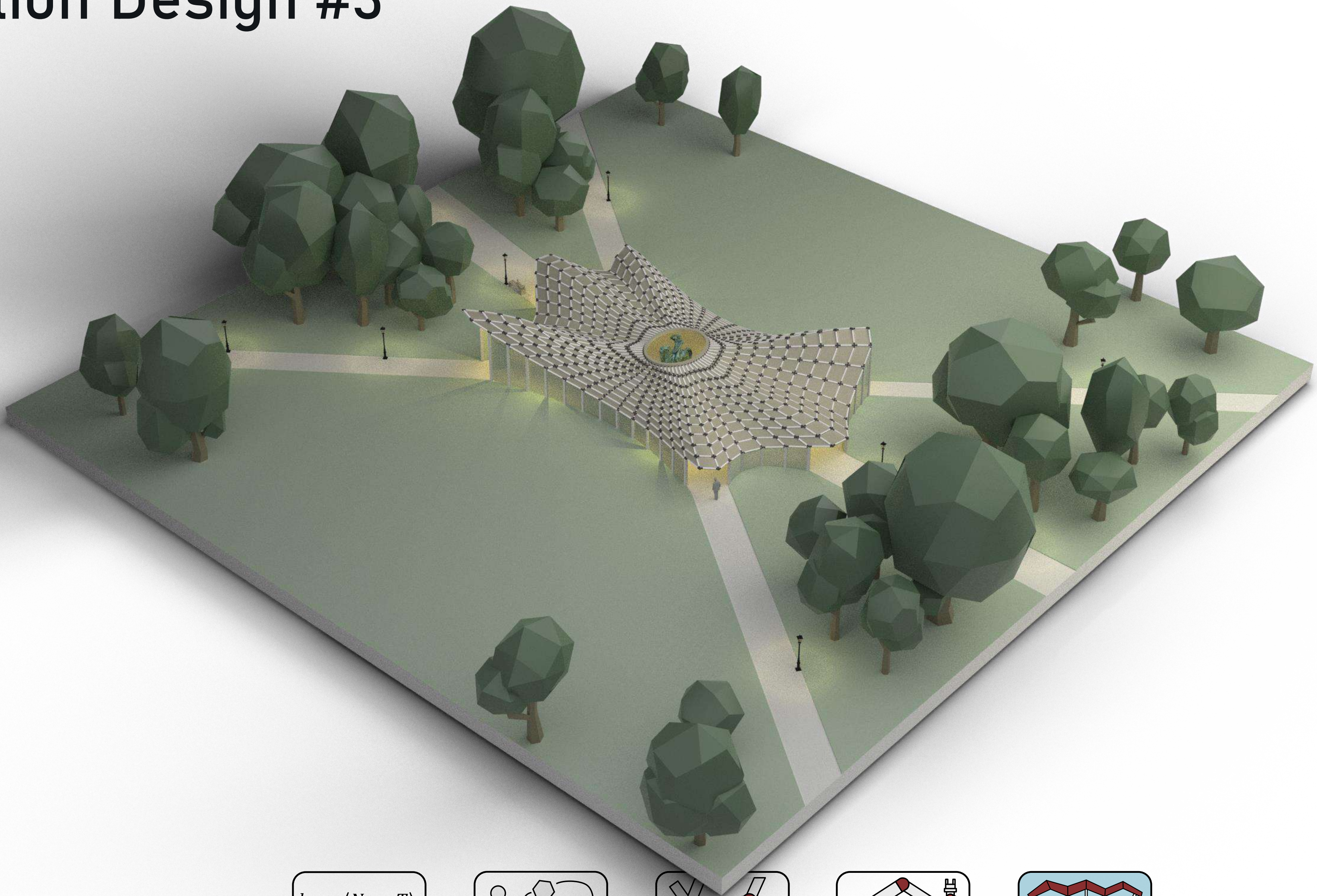


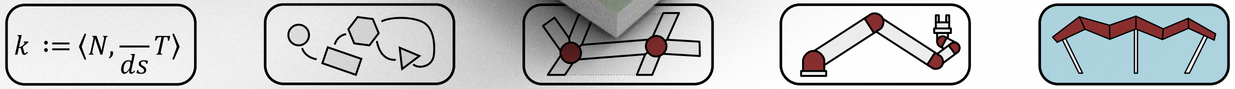
Pavilion Design #2



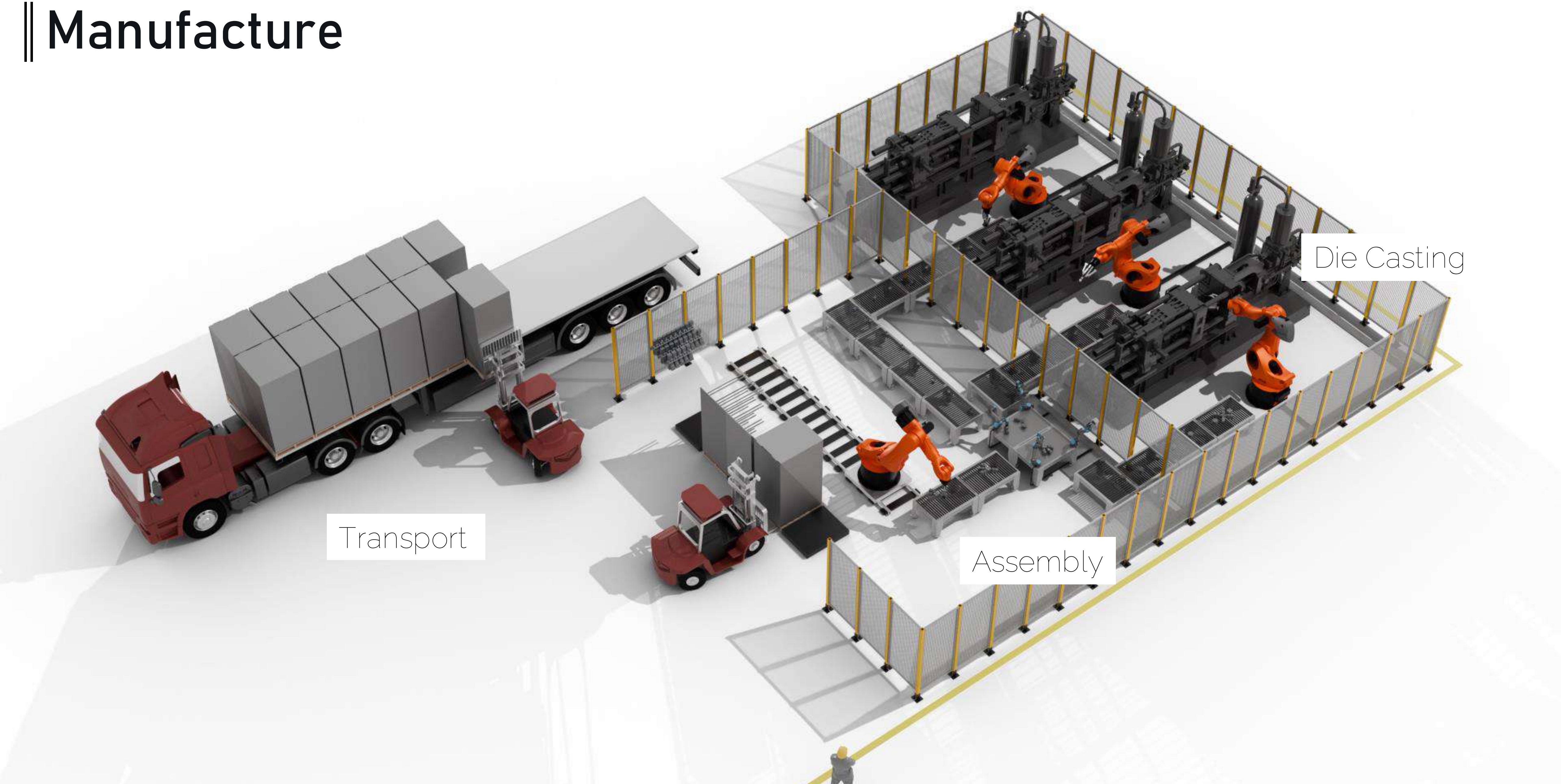


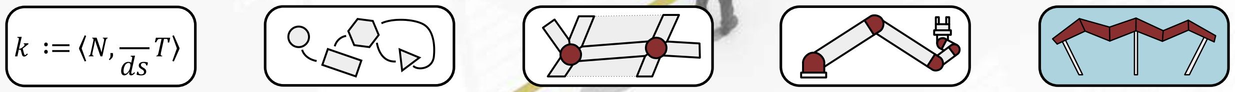
Pavilion Design #3



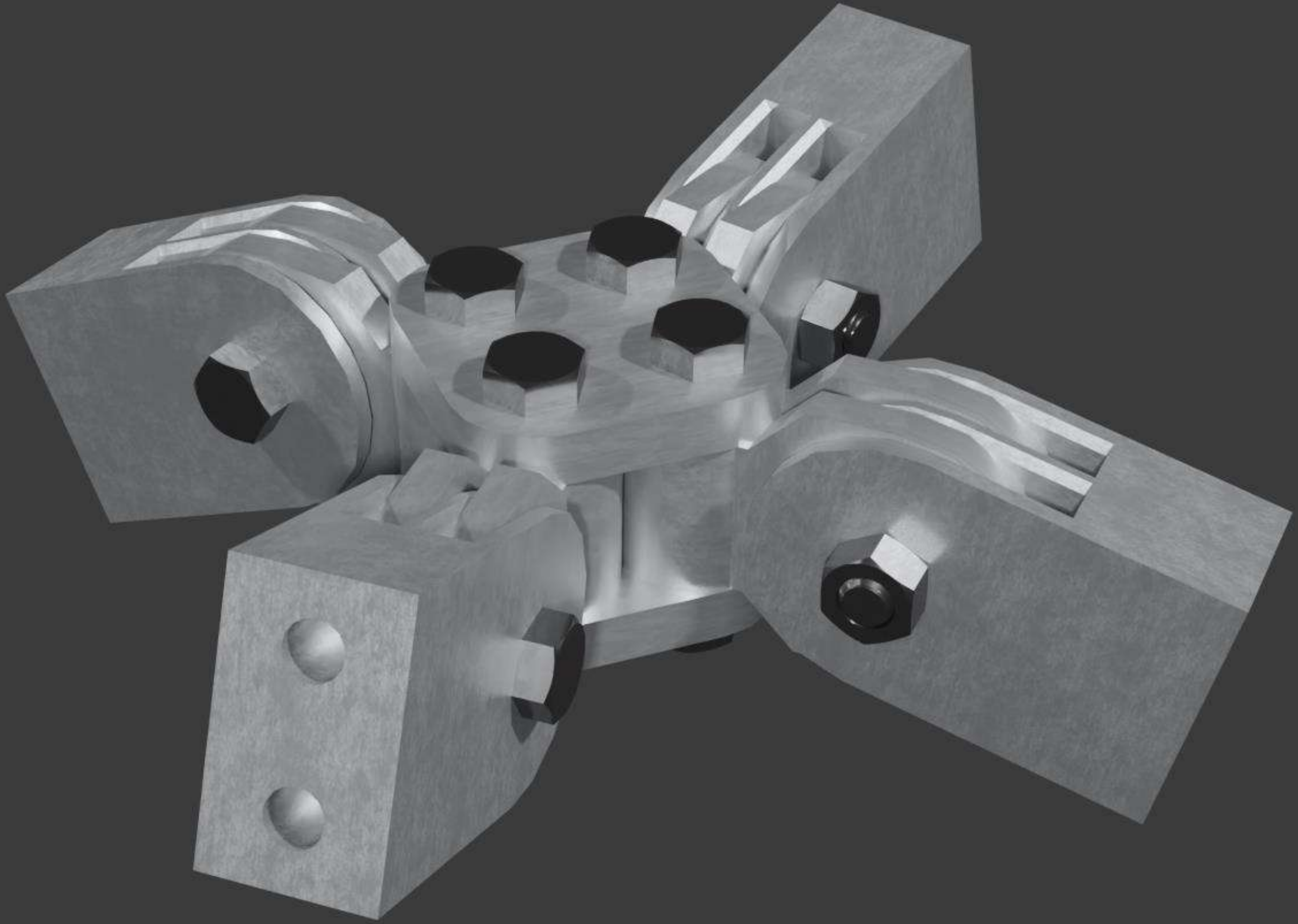


Manufacture

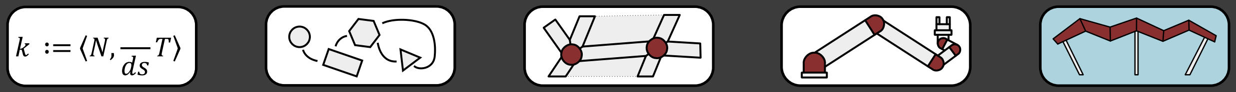




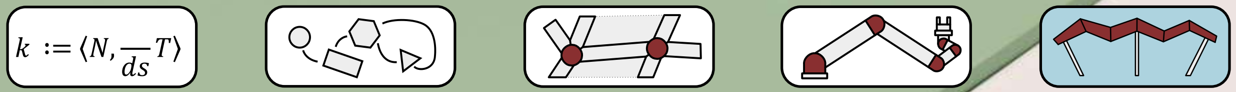
Friction Lock



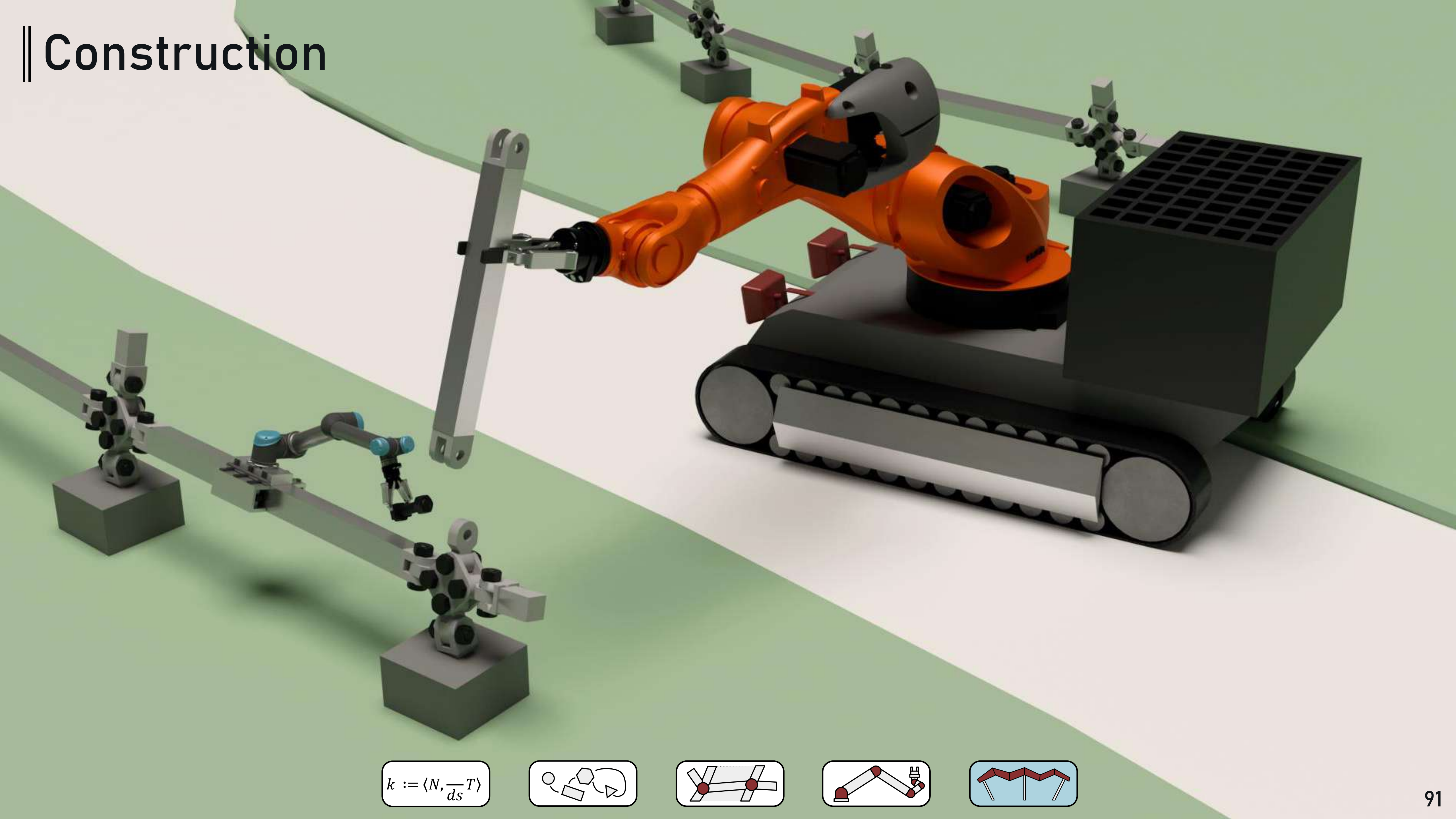
- Geometry
- Friction coefficient
- Force



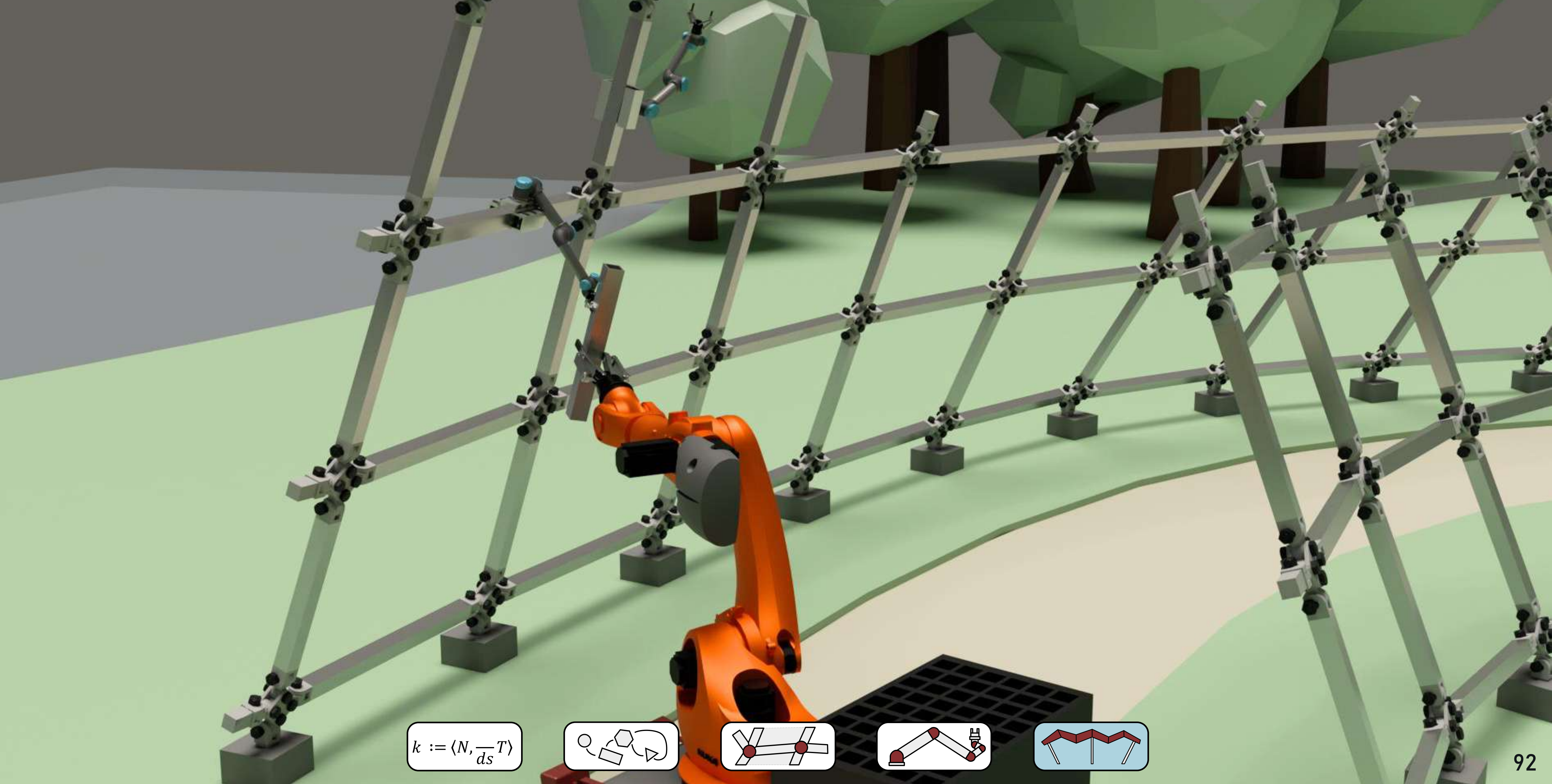
Construction



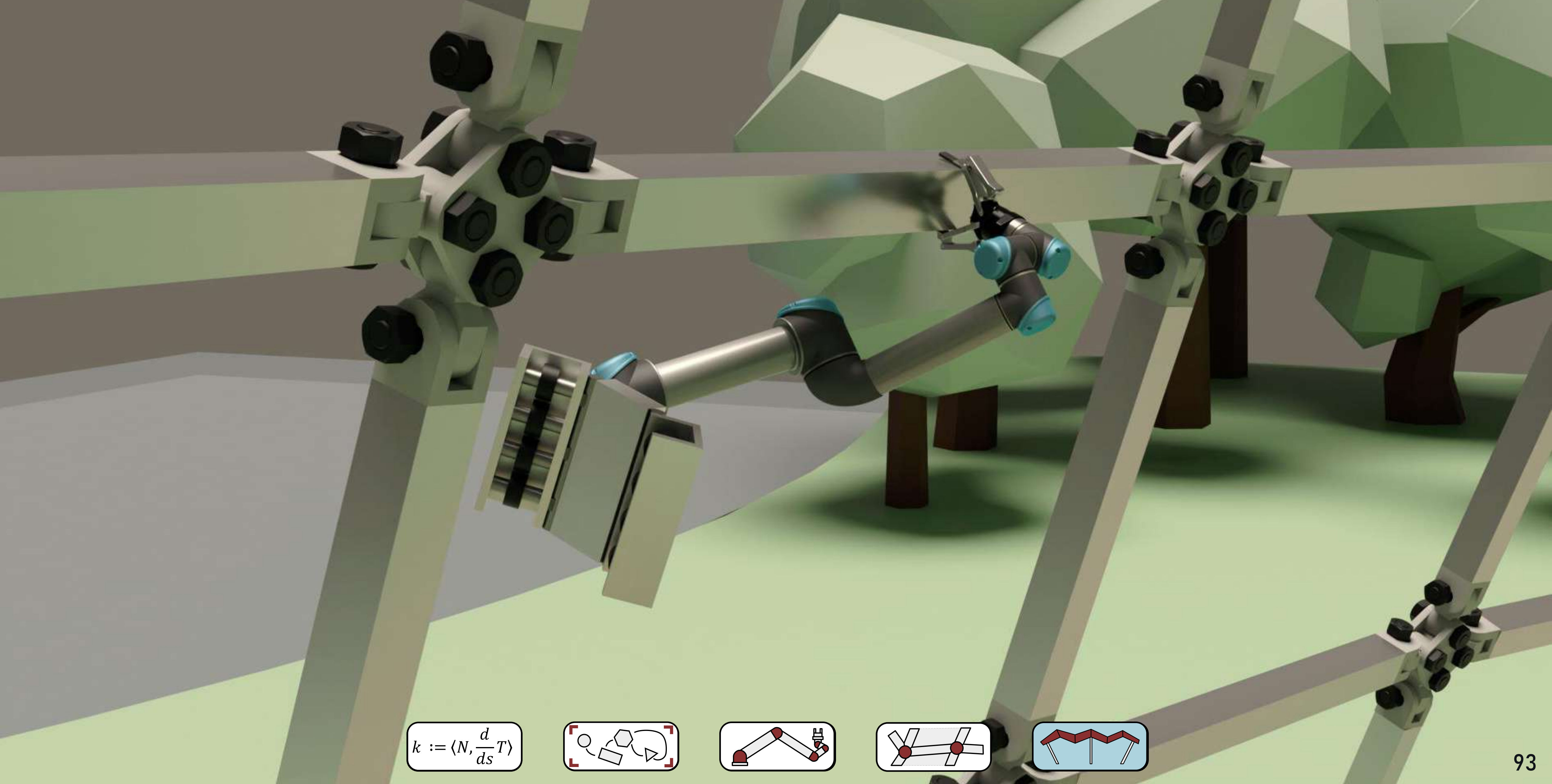
Construction



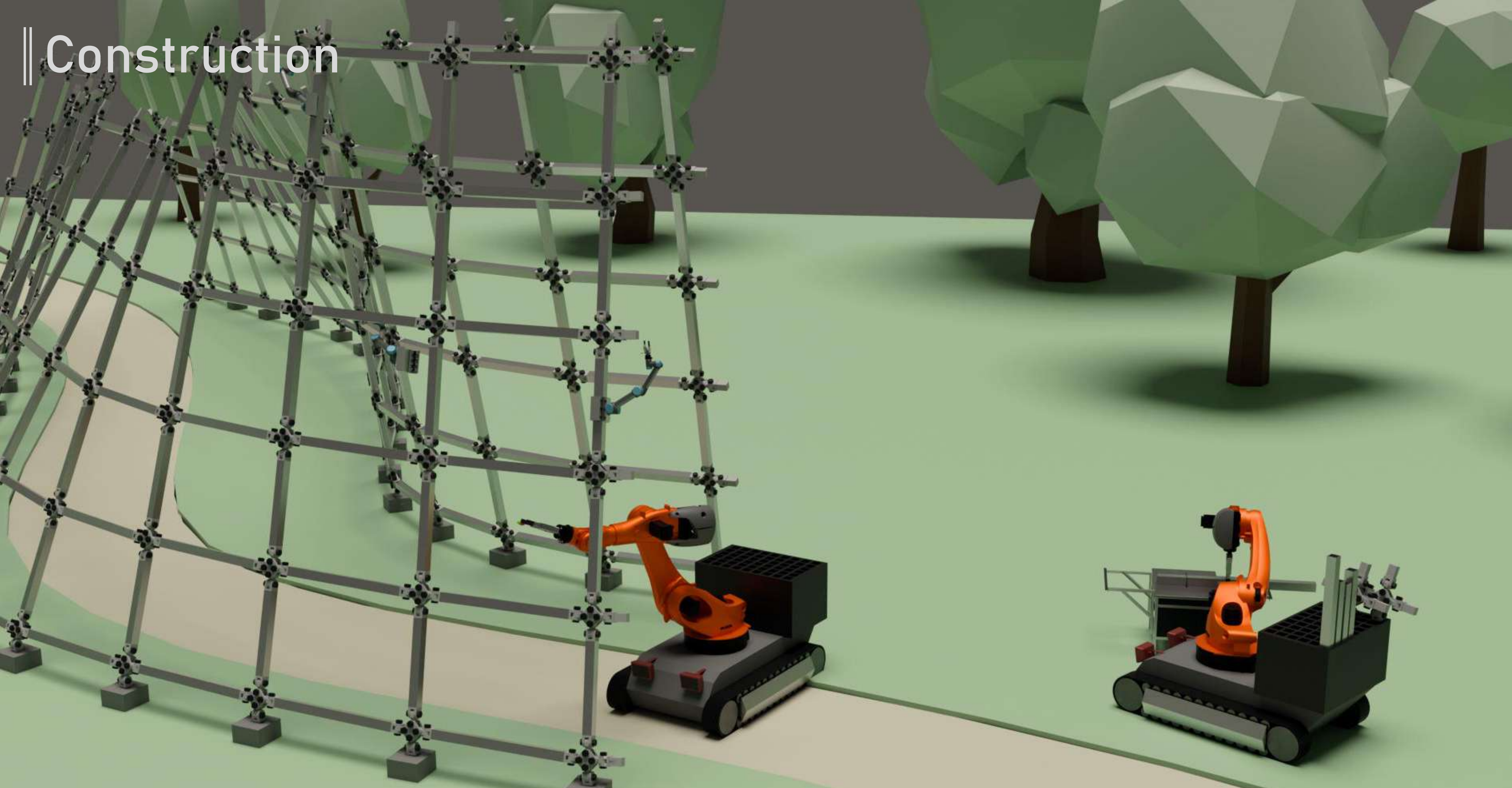
Construction

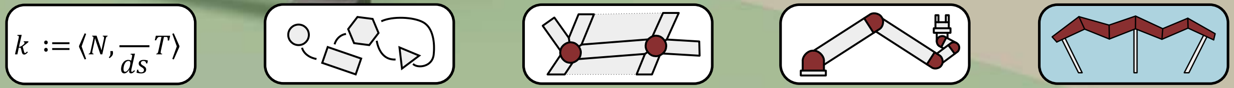


Construction



Construction





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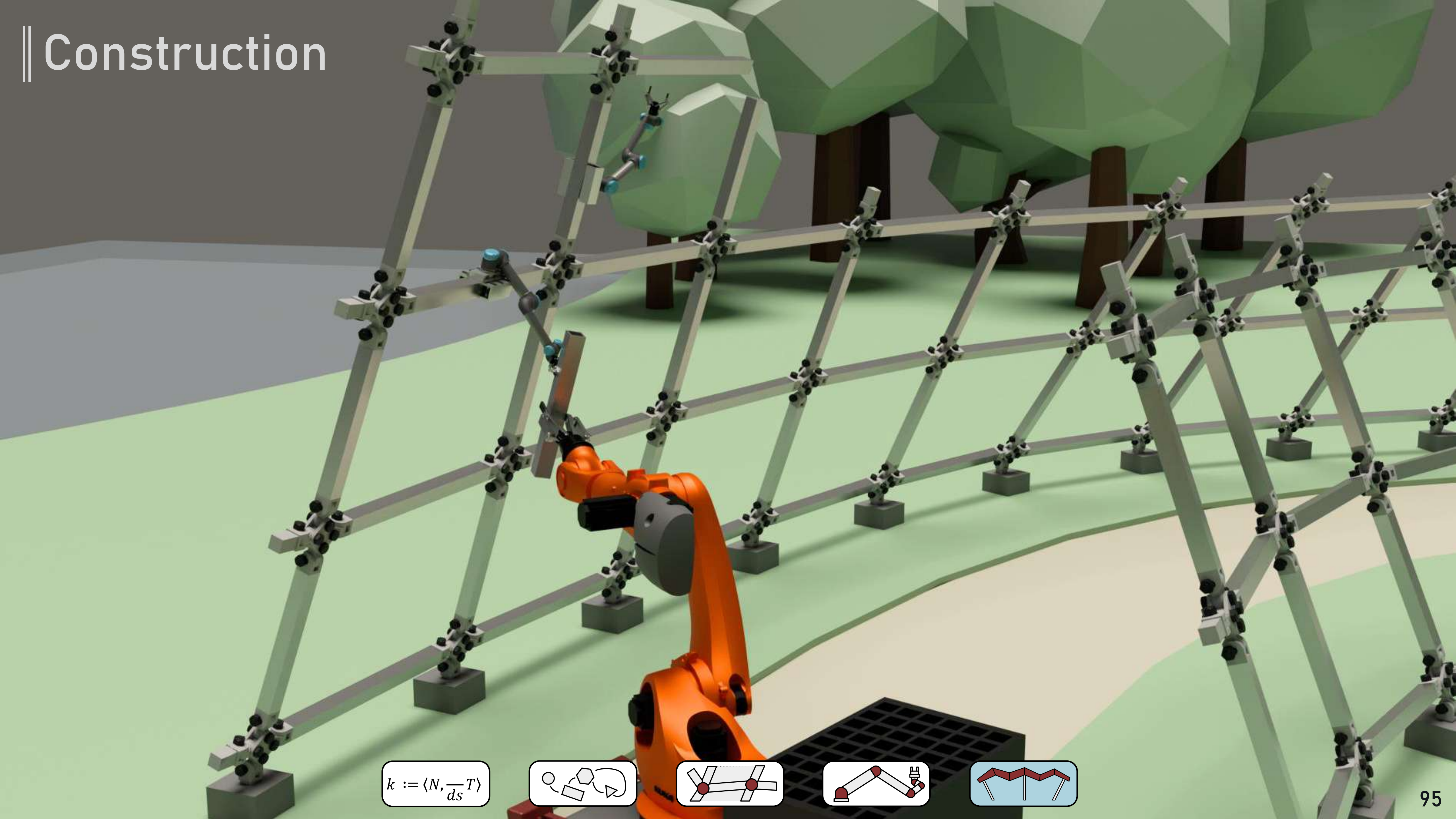

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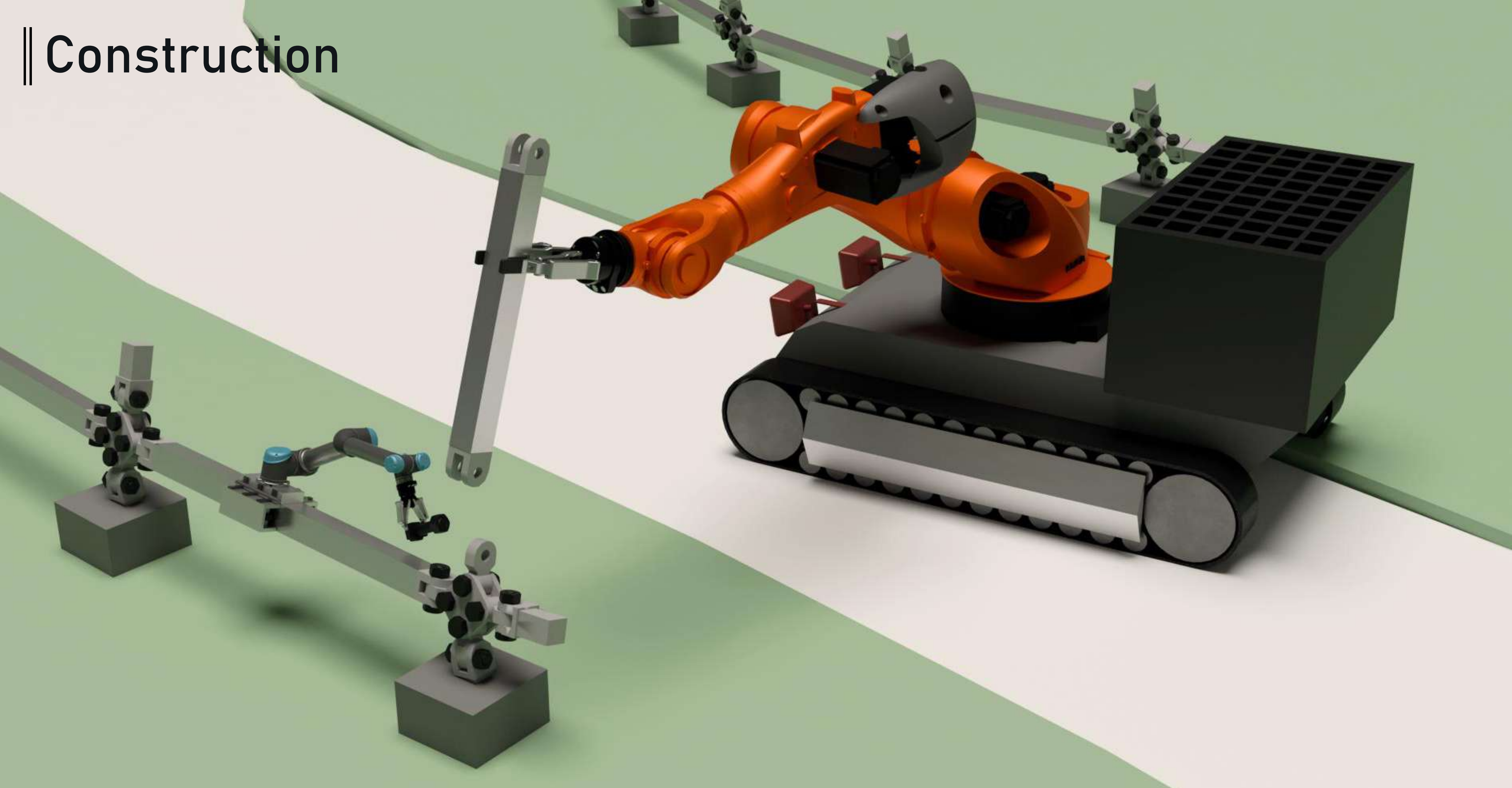

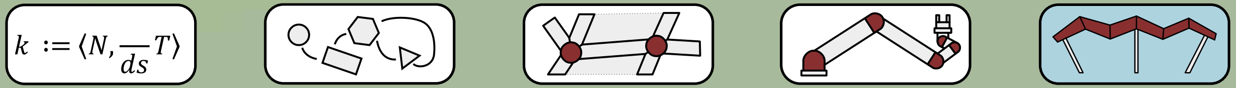

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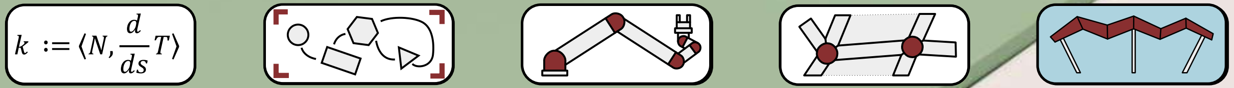

8 Conclusion

This thesis introduces a novel reusable node & beam system for use in the automatic assembly of freeform architecture.

Discussion

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The most significant limitation of the current node & beam system is the non-researched integration of facade panels.

A crucial aspect is whether the strength of the node's friction lock is sufficient for the forces in a facade

An additional node should be designed with a torsion axis for the system to be able to adapt to any shape

Future Research - facade

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The effect of small unresolved torsion on the accuracy of the system should be further explored

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Multi disciplinary collaboration would be a great boost to the local research and should be sought out