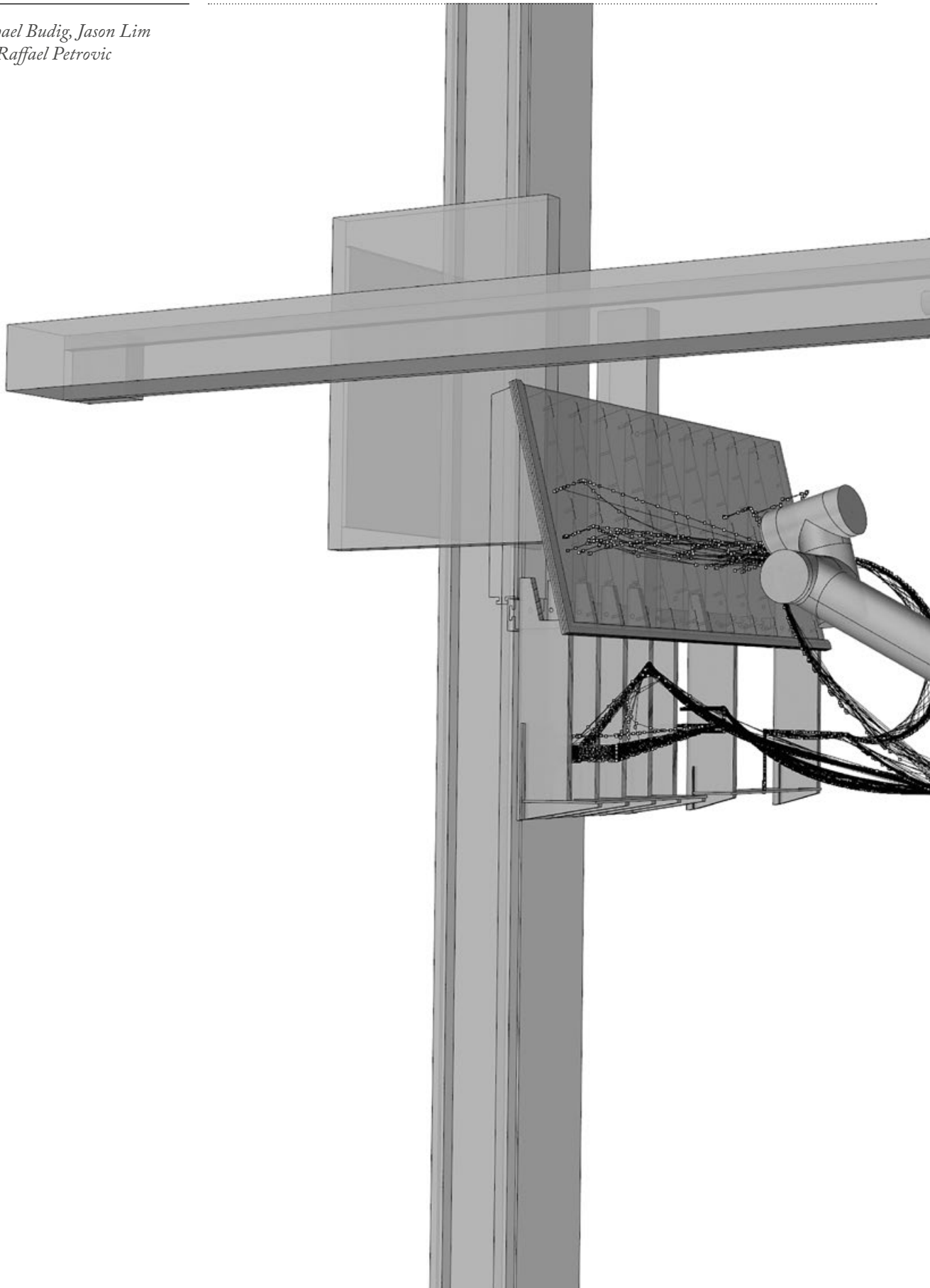


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*Michael Budig, Jason Lim  
and Raffael Petrovic*

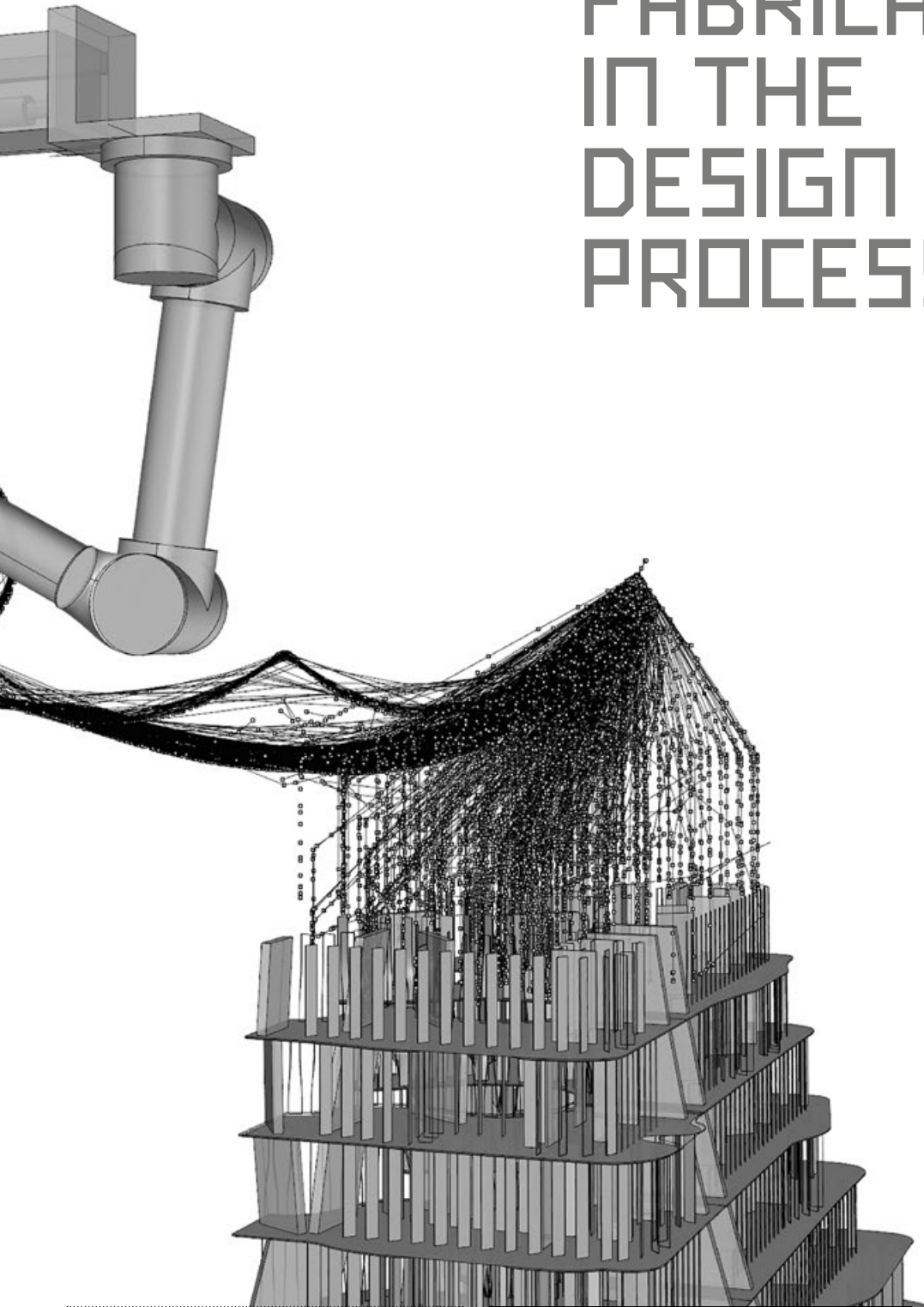


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Robotic fabrication paths building a 1:50-scale model, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

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# INTEGRATING ROBOTIC FABRICATION IN THE DESIGN PROCESS



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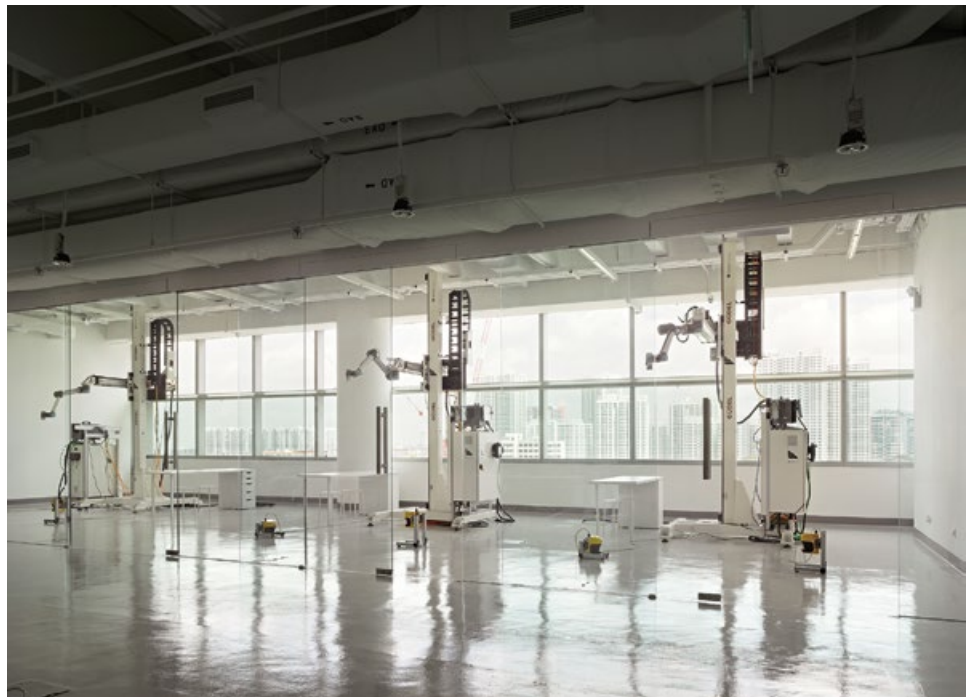
The production paths can be anticipated to avoid possible collisions of the robotic arm with the already assembled components, and actual paths can be recorded to check for possible optimisation in the building process.

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Does the application of robotic technologies in Southeast Asian cities, where the residential high-rise is pre-eminent, provide a unique opportunity to introduce bespoke design elements and liberate the high-rise from serial production and standardisation?

**Michael Budig, Jason Lim and Raffael Petrovic** of the Future Cities Laboratory (FCL) at the Singapore-ETH Centre for Global Environmental Sustainability (SEC) introduce the research project 'Design of Robotic Fabricated High Rises' (2012–13) led by Fabio Gramazio and Matthias Kohler, exploring high-rise typologies and architectural scenarios for future vertical cities.

Fast-growing regions in Southeast Asia and China face a continual demand for housing. In cities like Singapore, high-rises represent the most common residential typology. Around 80 per cent of Singapore's population live in flats, which have been erected by the Housing Development Board (HDB). Similarly to Hong Kong, these programmes were initiated from the 1950s onwards to provide housing for millions of people in a very short time. High-rises foster a strictly repetitive distribution of identical building elements along the vertical axis, and thus ideally fulfil the efficiency criteria of a still dominant industrial building paradigm. The result is very often reflected in overly uniform urban environments. The research project Design of Robotic Fabricated High Rises investigates the potentials of robotic building processes for the construction of this typology. The hypothesis is that robotic technologies in combination with computational design techniques liberate this widespread building typology from the limitations of a serial production paradigm. Professors Fabio Gramazio and Matthias Kohler lead the research project, which is one of 13 different modules of the Future Cities Laboratory (FCL) at the Singapore-ETH Centre for Global Environmental Sustainability (SEC).<sup>1</sup>



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Robotic facilities, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

The robotic facilities at the Future Cities Laboratory are used by masters-level and PhD students for research on digital fabrication processes at different scales.

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The research is conducted on two distinct levels, which constantly inform each other. PhD researchers approach the subject from a scientific perspective, focusing on the integrated development of computation, fabrication and material systems. In parallel, a design research studio explores the impact of such changed production conditions on architectural design, with small groups of master's-level students designing parametric high-rise typologies and creating architectural scenarios for future vertical cities.<sup>2</sup> An experimental methodology is applied in the studio, whereby designs are explored using computational techniques and materialised through robotic fabrication. Two ideas are central. First, 1:50-scale models serve as the primary medium for design exploration. Second, rather than designing forms, the focus is set on designing processes, which are algorithmically described and robotically executed. The objective is to expand present computational design methodologies, which are already well established in academia, by introducing a material counterpart in the form of robotically fabricated physical working models.

### The Role of the Physical Model in Computational Design

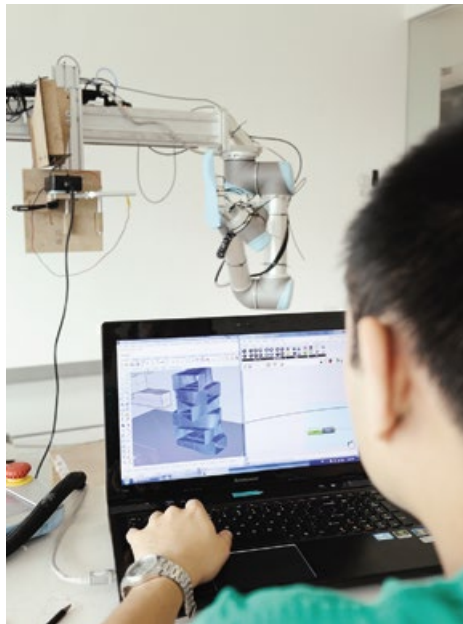
Computer-aided design (CAD) technology has advanced rapidly in the past two decades and is now widely adopted by architects. Today, digital models can be produced faster and cheaper than physical ones. Despite being represented on a flat screen, the digital model appears to be three-dimensional since it can be rotated, moved and navigated in real time. Furthermore, it can be rendered to produce photo-realistic still images. With these qualities, the digital model has undermined the primacy of the physical model as a representational device. At the same time, it has also largely replaced the working model, as it is easy to edit and thus even more suited for quick iterative design exploration than its physical counterpart.

While a digital model can potentially contain all construction details down to the smallest component, a scaled physical model can only embody a limited amount of information. However, despite this intrinsic limitation, physical models retain distinct advantages over digital ones. Working models provide architects with a direct and physical means to study and understand the three-dimensionality of their design, which cannot be fully grasped through a two-dimensional digital representation. In order to elaborate specific design ideas in a working model, architects have to choose an appropriate level of abstraction. While building them, they sharpen the key concepts of the design. In addition, the physical model immediately communicates the relationships between material and structure, space, and proportions. It provides architects with direct sensual and haptic feedback that is completely missing in a digital environment.

Thus, the thesis of the design research studio is to reposition the physical model as a critical explorative tool in conjunction with computational design, whereby robotic technology is used for its fabrication. With its ability to execute

individualised actions and to position elements in space without external reference systems, the robot enables students to build models using complex assembly logics, out of a large number of parts and within a reasonable amount of time. In contrast to 3D-printed models, which are based on an undifferentiated, layer-based fabrication process, robotically fabricated models bring into focus structure and tectonic characteristics. In this regard, they offer to the designer the same kind of insights as their handmade equivalents. However, robotic fabrication creates a direct and rigorous link between the physical model and its computational origin.

A 1:50 model scale was chosen as it exposes explicit structural and constructive problems, and allows students to explore articulated architectural solutions. Standing up to 3 metres (10 feet) tall, the model towers in the design studio become 'buildings, with their own complex engineering and construction problems'.<sup>3</sup> They are evocative physical expressions of a design approach that combines abstract digital thinking with concrete tectonic sensibility.



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The thesis of the design research studio is to reposition the physical model as a critical explorative tool in conjunction with computational design, whereby robotic technology is used for its fabrication.

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Student controlling the robotic fabrication process, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2013

The robotic controlling components are embedded in a visual programming environment. The student checks the conceived model with the physically fabricated element and incorporates adjustments into the digital model.

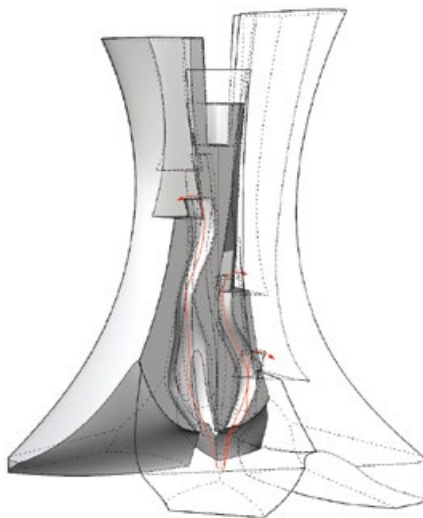


## The Design of the Robotic Process

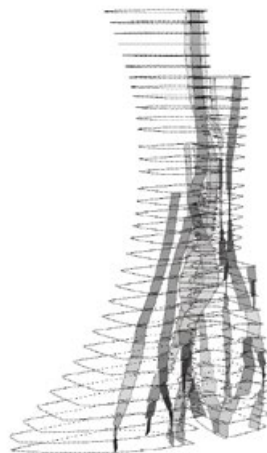
The industrial robot has been designed as a general-purpose machine. Hence, it must be customised for a specific application, in this case model fabrication, through physical tooling of specific end effectors and peripheral tools. With a suitable end effector attached to its tip, a robot is able to manipulate material for a bespoke constructive process. The robotic facilities at the Future Cities Laboratory have been conceived as an open environment in which the robots can be extended by the students with a kit of modular parts, including grippers, material feeders and feedback sensors. This allows a wide range of design experiments to be supported. Unlike their larger industrial counterparts, the robotic arms installed in the design studio are safe to work with, enabling direct human-robot interaction. They are mounted on vertical axes, enlarging their working envelope and allowing for the fabrication of tall study models.

In addition to the physical tooling of end effectors, robots, like any computer-controlled machine, can be programmed in their movements. But the production of control data in the form of coded machine instructions requires programming skills as well as an understanding of robotics concepts such as kinematics, which lie outside most architects' domain of expertise. To address this problem, the custom robot programming library *YOUR*, which aims at making robot control intuitively accessible to students, has been implemented. Based on this, a toolkit of visual programming components for Grasshopper™, allowing students to directly assemble graphical components for the control of their robotic fabrication sequences, was developed. Due to its immediacy, this visual programming approach is well suited for quick prototyping of initial, simple robotic processes. As the text-based code defining these components is transparent and accessible, once students acquire experience in programming and knowledge in robotics, they become able to modify them in order to introduce more complex flow structures and logics into their robotic processes.

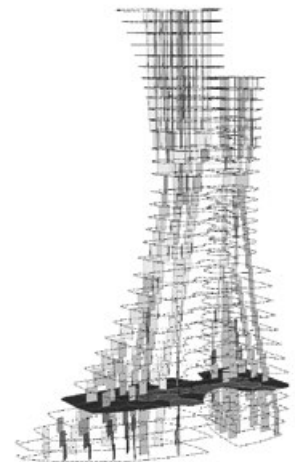
Unlike their larger industrial counterparts, the robotic arms installed in the design studio are safe to work with, enabling direct human-robot interaction.



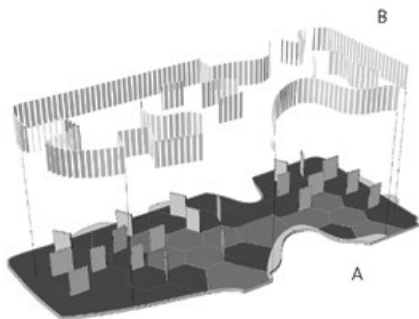
1. Generation of outer volume and inner voids



2. Creation of primary wall system



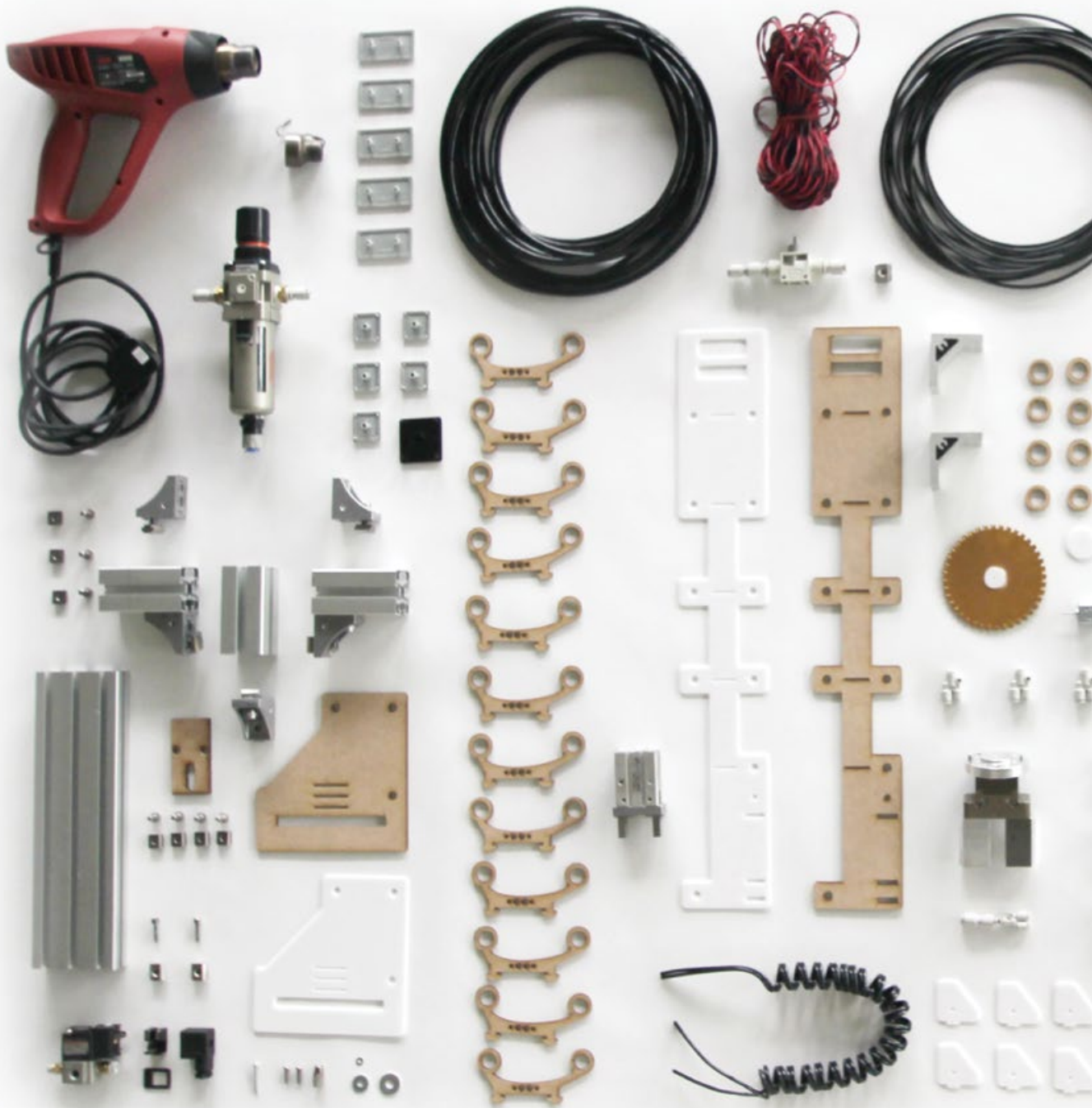
3. Generation of secondary wall system



4. Population of interior walls with informed louvers



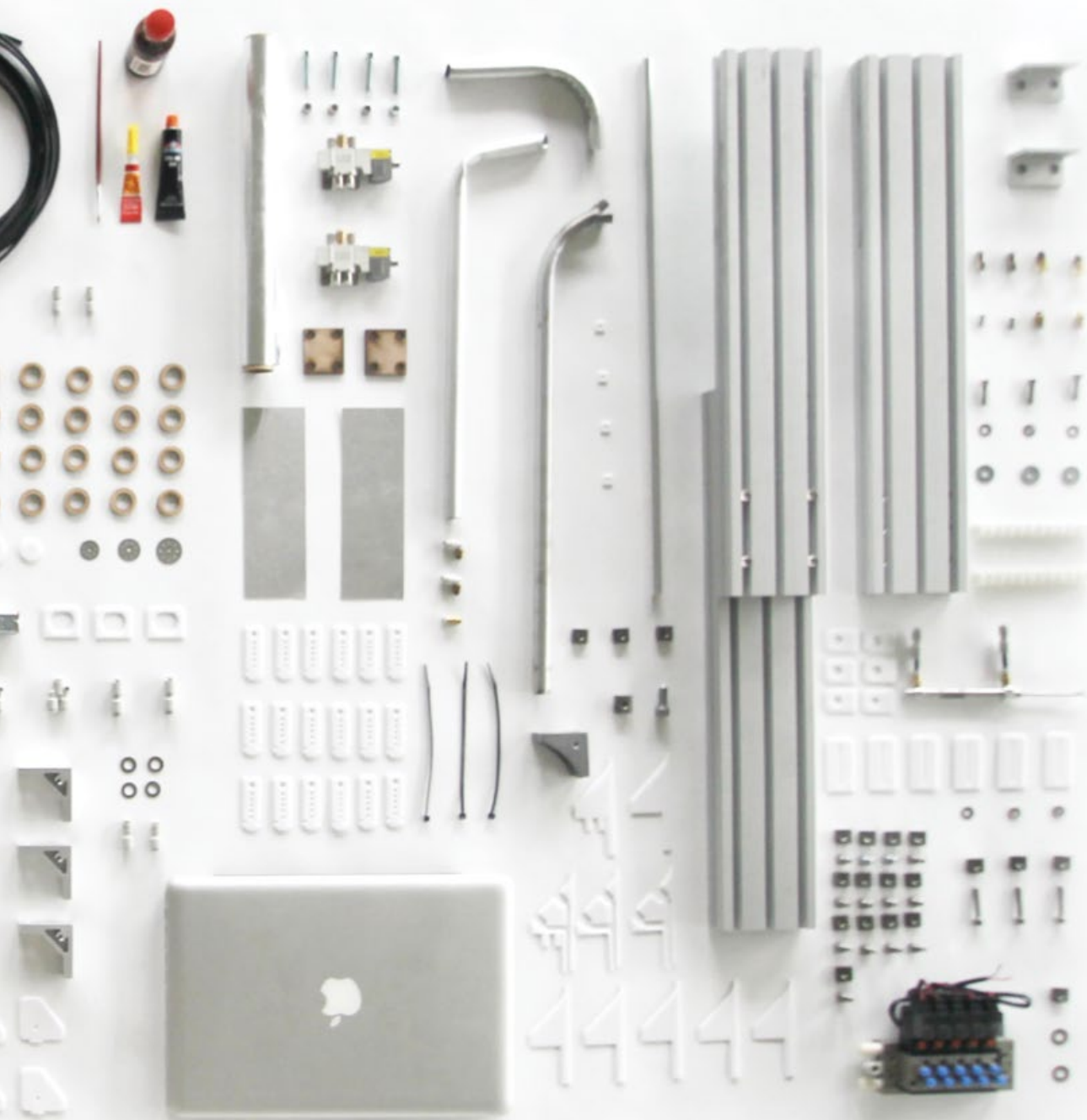
5. Final tower



Sylvius Kramer and Michael Stünzi, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

Dismantled setup of a robotic end effector, developed for bending acrylic strips through thermal deformation. Students were able to interact directly with the robotic systems, adjust the end effectors to their needs, and eventually invent setups for various fabrication and assembly processes.

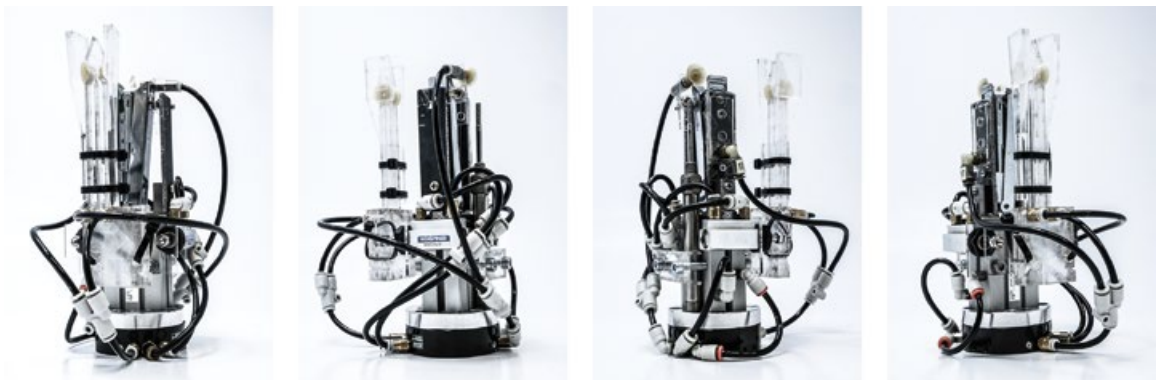
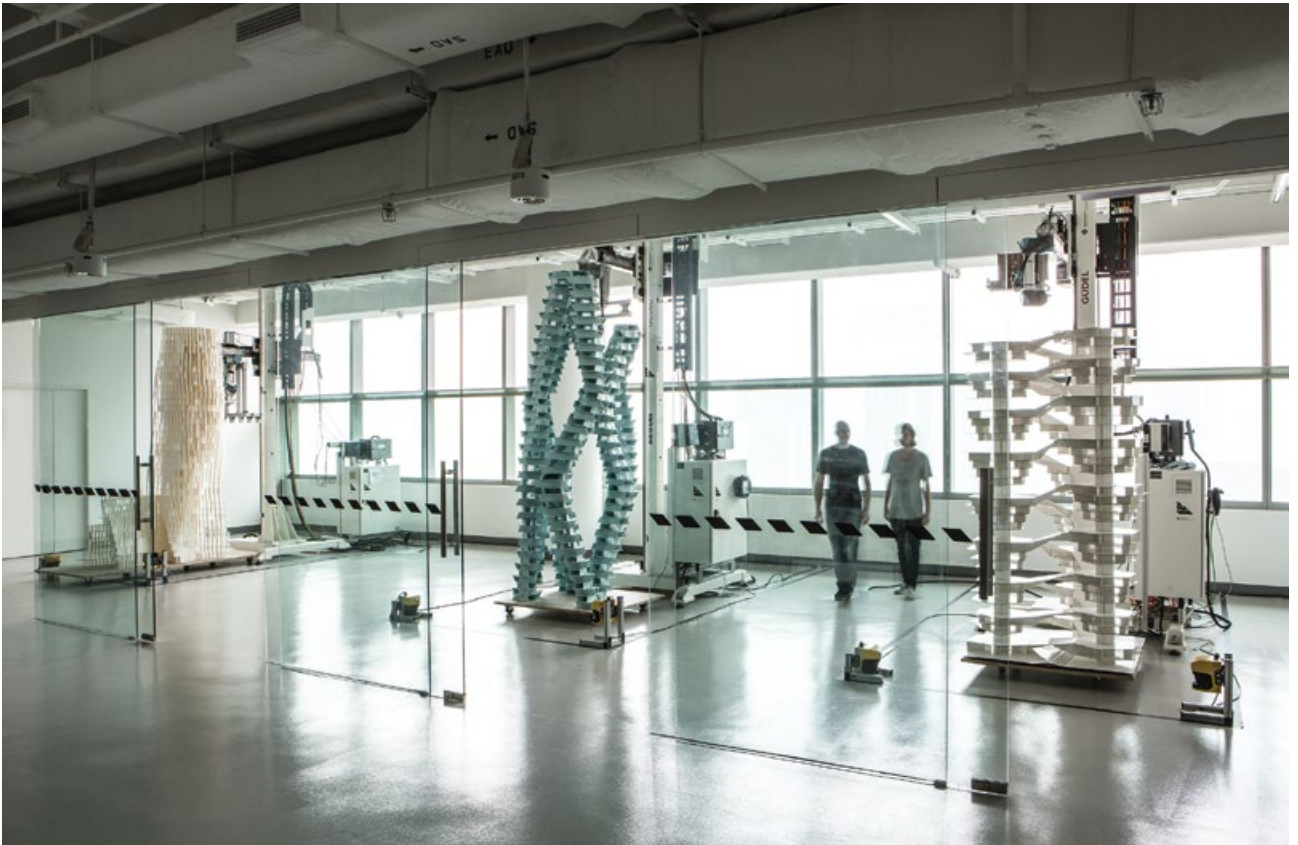






Robotic fabricated models at the robotic facilities after completion, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2013

Each student team had one robotic facility for the development of their designs, and for the fabrication of up to five generations of 1:50-scale models.



Sebastian Ernst, Sven Rickhoff and Silvan Strohbach, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

Series of robotic end effectors were developed for various materials and constructive systems. The illustrated gripper was conceived for a robotic stapling process, which clamps two paper strips. Since the two paper strips can be pushed forward with varying speed between two clamping locations, the material is forced to bend, producing curvilinear shapes.

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## The Integration of Computation and Fabrication

The design research studio sets the emphasis on designing processes, which integrate design computation and robotic fabrication, as opposed to directly designing forms. Students develop their architectural concept along with a specific computational design strategy and a custom robotic fabrication process. While the parallel development of computation strategies and fabrication processes sharpens the students' awareness for their conceptual interdependence, their synthesis results in digitally driven yet tectonically informed designs.

In order to become able to computationally formalise their ideas by means of either visual programming or scripting, students first have to identify the relational logics underlying their architectural concepts. The resulting computational models do not only encapsulate the design logic, but also incorporate the procedure for their digital robotic fabrication. Thereby, the students are not only able to generate and visualise the geometry of their design, but can also produce the control data needed by the robot for their (scaled) digital production.

Robotic fabrication and computational design augment each other in several ways. In addition to the direct materialisation of digitally conceived designs, the physical working model provides students with a differentiated and sensual feedback on their design, whereby they can immediately engage with its constructive and structural aspects. As part of an iterative process, these insights can then be re-integrated into the computational design strategy.

Once the connection between the computational model and the robotic fabrication process is operational, this design methodology allows for the stepwise refinement of the design through the sequential fabrication of multiple working models. By iteratively refining the rules and tuning the parameters of the computational model throughout the design development, multiple versions can be physically evaluated and compared.

As the constructive capabilities of the robotic fabrication process clearly define the design space and thus productively inform the computational design strategy, its development can also be recognised as a creative act of design on its own.

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## Potentials of Robotic Technologies for Design Practice

The discussed methodology was tested over two consecutive one-year-long master's-level design research studios. The results, some of which are featured over the following pages of this issue, demonstrate the potential of the integration of robotic fabrication technologies into the computational design process of large-scale architectural typologies. This methodology directly addresses the shortcomings of contemporary digital design practices that overly privilege computation, by offering an alternative that stresses its complementary relation to physical (model) making.

The achievements of the studio were wide-ranging: compelling architectural concepts were developed, complex physical models were built and bespoke fabrication processes were engineered. Though less tangible, the most significant result is to be found in the increasing awareness of computational logics among the students exposed to this design methodology. After acquiring the skills to productively use computation and digital fabrication for design purposes, by developing their projects they learned to synthesise their thoughts in algorithmic logics and to translate them into material, constructive processes.

Architectural design practice will be increasingly mediated by digital technology in the future. Digital fabrication technology allows architects to conceive designs both digitally and physically, and may empower them to take a more active role in the materialisation and construction process.

As a consequence, students today must become acquainted with such technologies as part of their education. Only then will these architects-in-the-making be equipped with the technical and, more crucially, intellectual skills, to navigate and actively influence this new technological landscape.

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### Notes

1. The SEC is co-funded by the Singapore National Research Foundation (NRF) and the Swiss Federal Institute of Technology Zurich (ETH Zurich) Department of Architecture.
2. The design studio was conducted twice in 2012 and 2013 as a two-semester programme with students from both ETH Zurich and the National University

of Singapore (NUS). It was conducted by Matthias Kohler and Fabio Gramazio with Willi Viktor Lauer, Norman Hack and the authors.

3. Jane Jacobs, 'The Miniature Boom', *The Architectural Forum*, May 1958, p 107.

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As the constructive capabilities of the robotic fabrication process clearly define the design space and thus productively inform the computational design strategy, its development can also be recognised as a creative act of design on its own.

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# NESTED VOIDS



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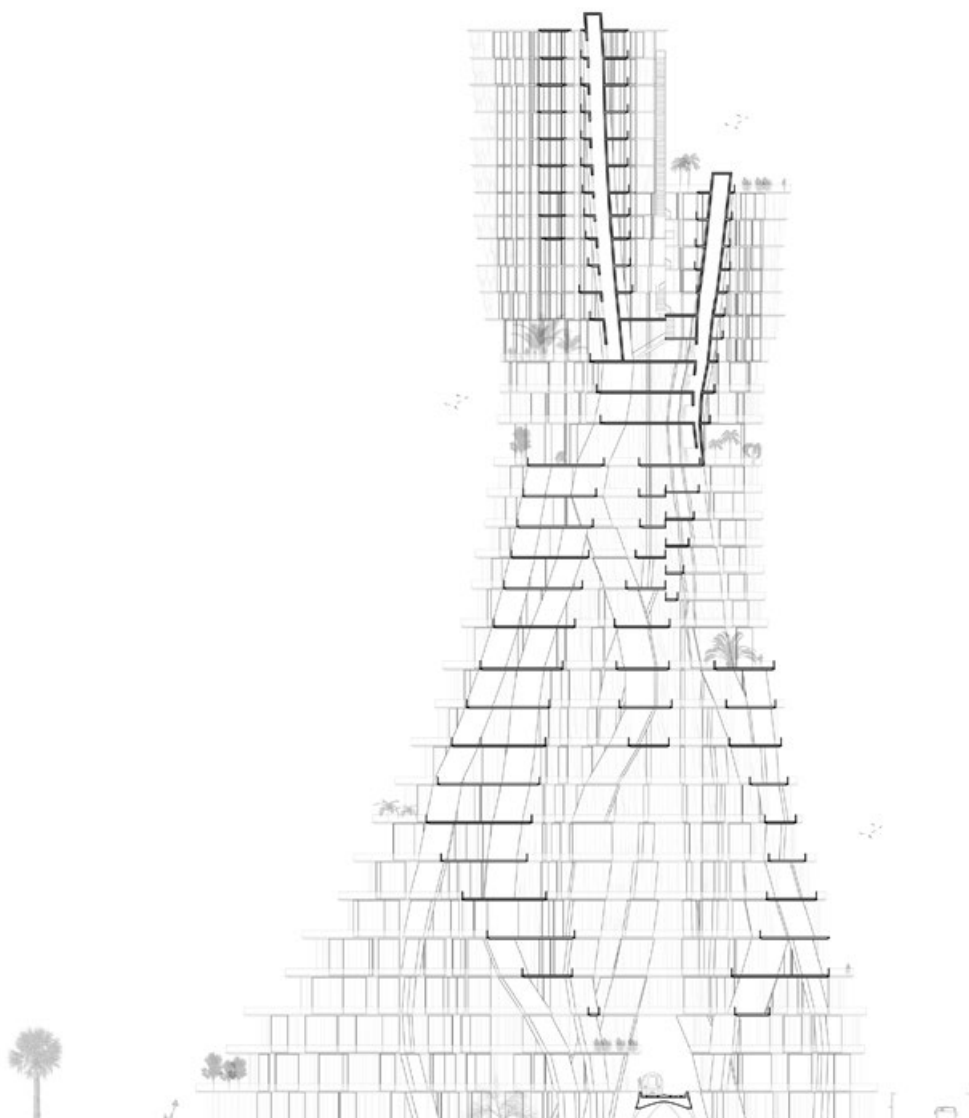
Pascal Genhart and Tobias Wullschleger, *Nested Voids*, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

The final 1:50-scale model is 2.7 metres (9 feet 10 inches) high and consists of several thousand uniquely cut and placed cardboard elements, and heat-deformed acrylic louvres.

The basic architectural idea of this project was to organise a high-rise through a system of interconnected voids, which contain the tower's circulation zones and shared spaces, provide natural ventilation and create visual connections between the floors. The design comprises a cluster of interacting towers, incorporating a railway station on its ground levels.

The integration of non-standard prefabrication and robotic assembly in an enhanced workflow enlarged the design opportunities, as the production and assembly of wall and floor elements have no longer been based on repetition. To control the resulting differentiated construction process, all the data for design, laser cutting, material deformation, and robotic assembly were generated in the computational environment. Later the robotic setup has been extended with a hot-air gun for thermal deformation, which was used to twist acrylic strips for a sophisticated louvre facade system.

The section shows the tower's branching system of concrete walls, which is generated by an algorithm correlating to the interconnecting void spaces.



Pascal Genhart, Patrick Goldener, Florence Thonney and Tobias Wullschleger, *Nested Voids, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012*

The robotic fabrication process is based on the integration of non-standard element prefabrication and robotic assembly. The model's walls and floors are laser cut out of cardboard sheets, which are placed on a custom-designed feeder system (left). From there the robot picks the elements (centre), applies glue and places them directly on the model (right).



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# SEQUENTIAL FRAMES



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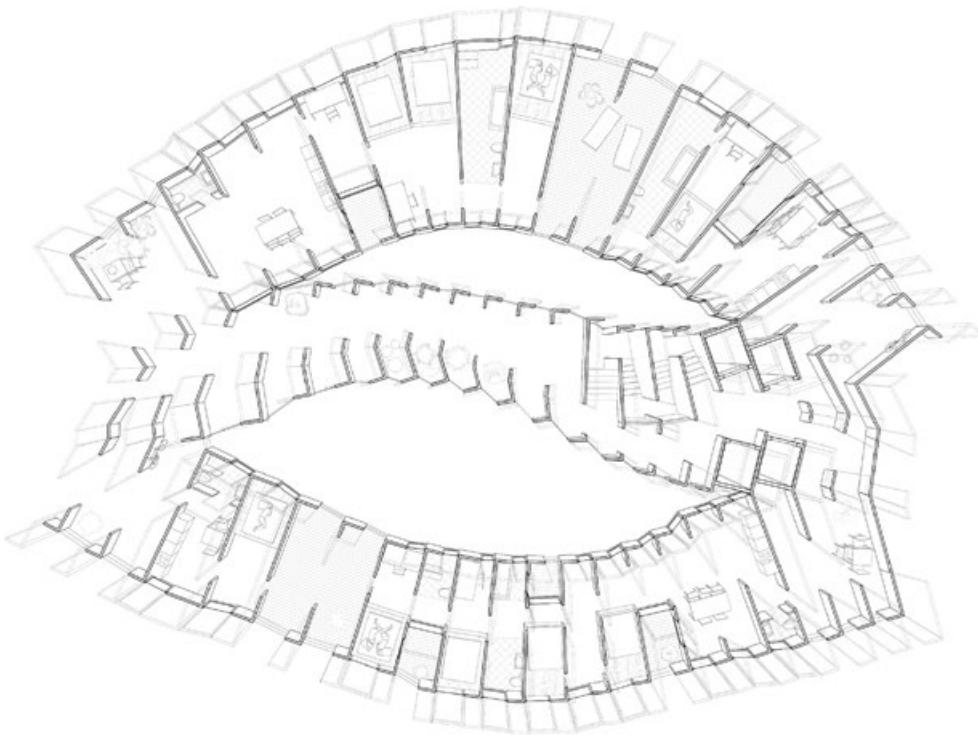
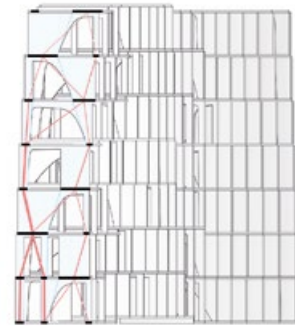
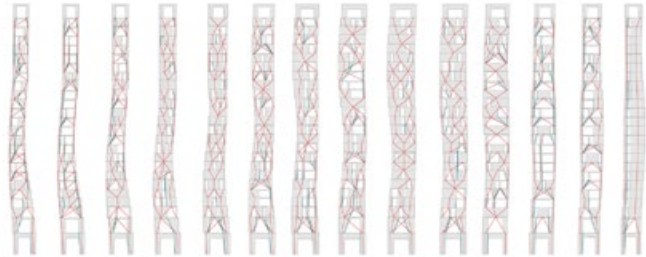
David Jenny and Jean-Marc Stadelmann, *Sequential Frames*,  
Design of Robotic Fabricated High Rises, Architecture and Digital  
Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre  
for Global Environmental Sustainability (SEC), 2013

The tower, 3 metres (10 feet) in height, is  
assembled out of 5,200 robotically cut and  
folded paper elements.

The design intention of this tower is to create a multitude of unique interior spatial experiences out of simple geometrical elements, by deploying the full power of computation. The towers are planned as linked strands that branch and merge into an undulating overall shape, bridging a Singaporean highway and connecting two adjacent parks.

Usually high-rises are designed as envelopes and then sliced into floors. This traditional approach is inverted by designing a tower starting from its interior spaces. In this project the number of shear walls was increased, and simple rules were experimented with to define their internal organisation. The design code distributes predefined openings into sequences of the shear walls to accommodate different flat types. In a second step the continuous force flow around these apertures is calculated from top to bottom. Each wall adjusts its opening's geometry, negotiating between the required structural performance and the desired cut-out for the flats, to make each flat appear different, even if they are all of the same type.

*top and centre:* Walls no longer frame a room but only a function. Interior spaces are not defined by enclosure, but by programmed cut-outs in a sequence of densely placed walls. The cut-outs follow the structural force flow.



*bottom:* By defining simple algorithmic rules for the distribution of openings in the shear walls, the design engine creates a high-rise with a wide variety of unique interior spaces.

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# VERTICAL AVENUE



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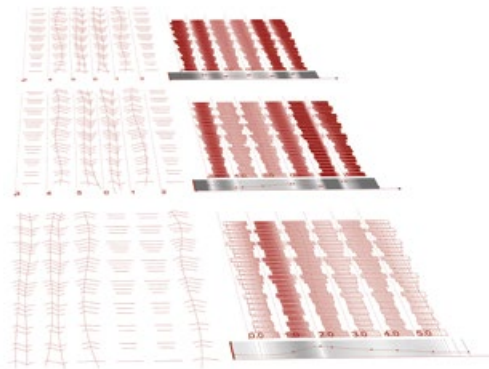
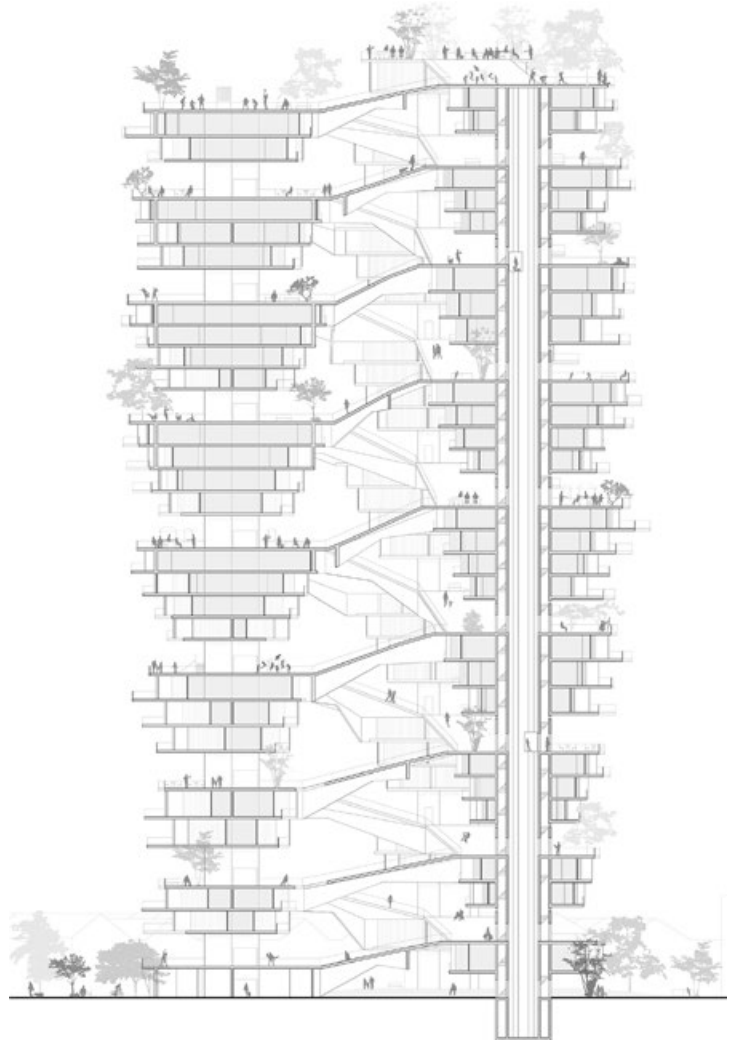
**Foong Kai Qi and Kan Lijing, Vertical Avenue, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2013**

The building consists of three high-rise towers with apartment clusters around the central cores. A system of staggered open public spaces is connected by a continuously upward-spiralling ramp, which serves as a public meeting space and park.

This project proposes a spiralling circulation system that provides public programmes and parks vertically throughout the tower. The idea is based on so-called 'void decks' – ground floors of Singaporean high-rise housing that are usually left open and used as public meeting spaces. The apartments are organised as clusters around three high-rise towers with vertically staggered void decks, that are connected by a continuously upward-spiralling ramp.

Apartments and facade elements are treated differently according to their positions in the towers. Flats oriented to the outside have cantilevering slabs that provide terraces and act as a shading system. All facades are set back to protect the units from Singapore's equatorial sun. Flats on the inside are enclosed with curved facade panels in order to deflect views and ensure certain degrees of privacy. All apartments have direct access to the nearest void deck.

Section showing the tower's continuous public circulation space.



The tower was assembled using sensor-assisted picking and placing, in combination with robotically controlled thermal bending of acrylic facade elements.



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# MESH TOWERS



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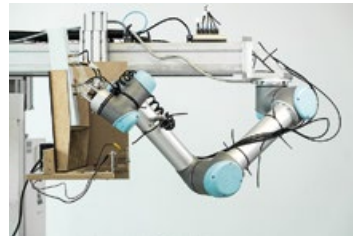
Petrus Aejmelaeus-Lindström, Chiang Pun Hon and Lee Ping Fuan, Mesh Towers, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2013

Individual residential units are generated on top of each other and oriented away from their immediate neighbours to provide privacy. The thickness of the load-bearing walls is locally adapted to the vertical force flow.

This project proposes a porous mesh of slender tower strands as an alternative to a massive condominium project, planned in direct neighbourhood to a conservation area of Singapore. The footprints of the overall shape are minimised, keeping the ground level open for a park and complementing the historical structure of its surroundings. The towers' nodes contain public programmes, such as restaurants, event spaces and kindergartens. Thin bridges connect these shared spaces, creating a hiking trail in the city.

For the final tower model, foam blocks are placed on a specially designed feeder. The robot cuts each of them differently, optimised to transfer the loads and shaped to accommodate various functions. This process in particular takes advantage of the robot's capability to accurately move and orient in space.

The robot picks the piece and moves it through a hot wire along a computationally generated path to fabricate each wall element.

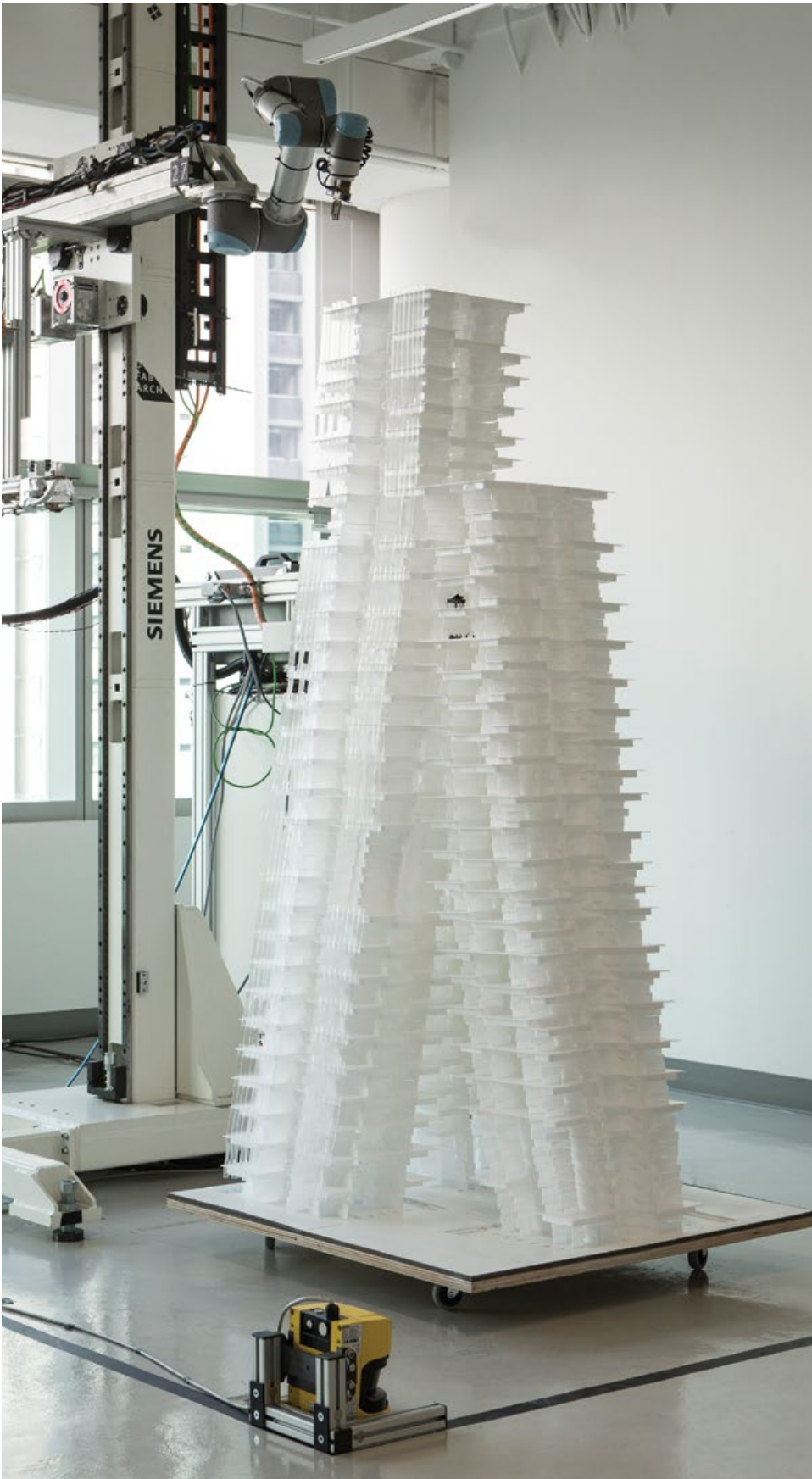


*The footprints of the overall shape are minimised, keeping the ground level open for a park and complementing the historical structure of its surroundings.*



The project consists of several slender towers merging and separating as they grow in height, structurally supporting each other.

# BENT STRATIFI- CATIONS



Sylvius Kramer and Michael Stünzi, *Bent Stratifications*, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

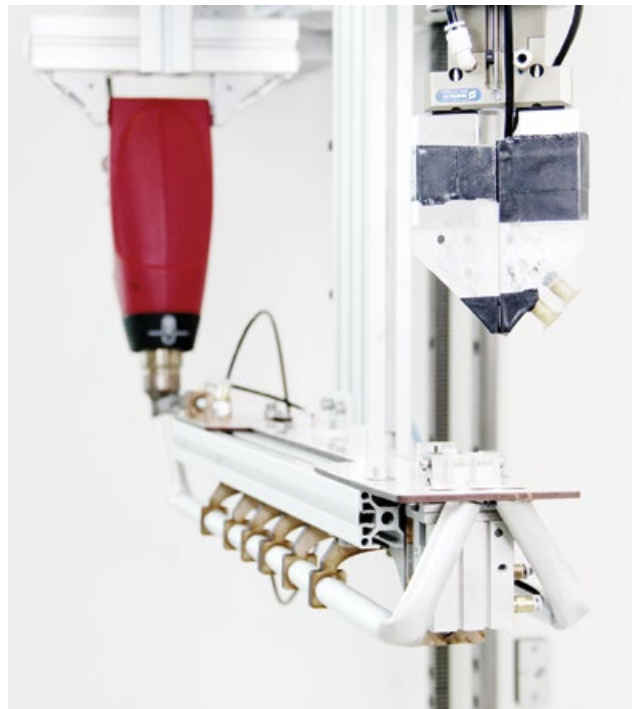
The bent acrylic strips are stacked on each other, in order to create the tower's primary structure.



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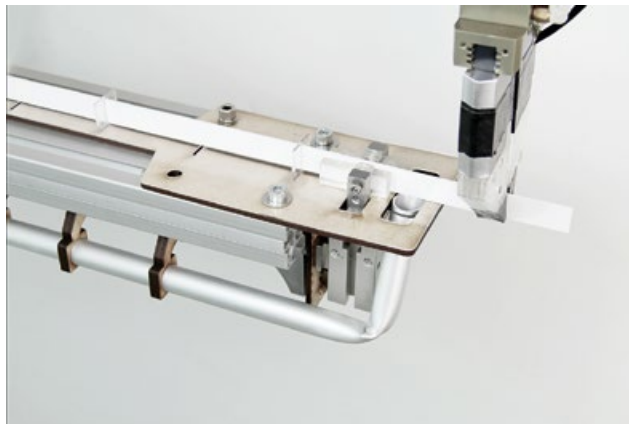
This high-rise building is designed as a cluster of three mixed-use towers, stabilised by leaning against each other. The project creates a new hub for an urban development area in the east of Singapore. It proposes a three-dimensional web of circulation and public spaces between the towers. The concept builds upon horizontal stratification and provides differentiated apartment types, including split-level.

The processes in this project were based on working with a high number of identical, small building components. The amount of elements thus shifted the focus to investigating more complex aggregation logics. The final model still consists of generic basic elements, but the standard acrylic strips are thermally deformed into unique geometries during the robotic assembly process. This simplified the preproduction of the elements, and enhanced the picking and placing process while robotically informing their shapes.



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*The processes in this project were based on working with a high number of identical, small building components.*



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top and bottom: Acrylic strips are fixed in a linear rail and pulled forward to a designated bending position. The material is heated up and then bent by the robot to any desired angle.



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# UNDULATING TERRACES



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Sebastian Ernst, Sven Rickhoff and Silvan Strohbach, *Undulating Terraces*, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012

The final tower investigates a robotic stapling process of paper strips to create the primary structure and form of the tower.

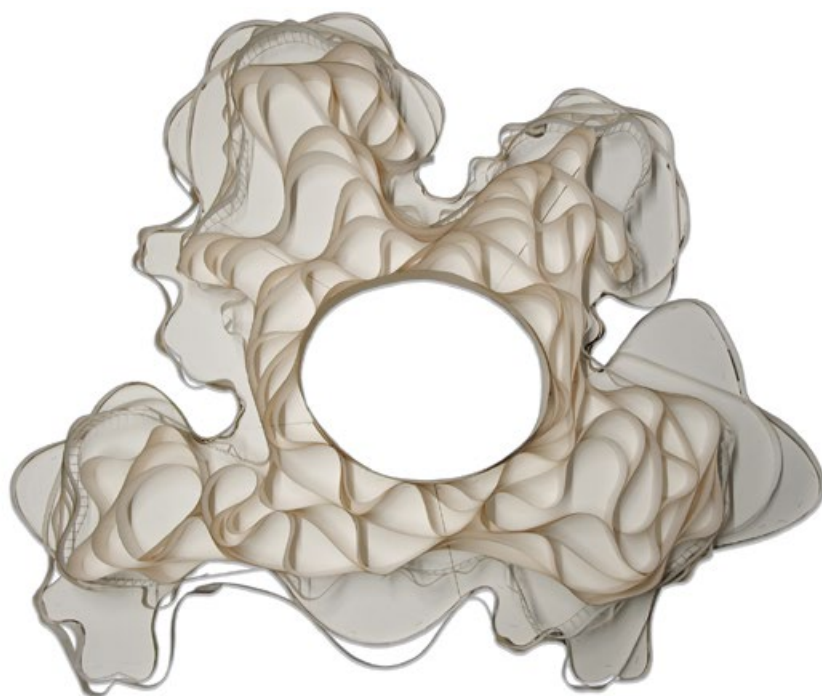
Residential units are organised between a large internal void and an exterior undulating facade containing terraces. The walls of the inner void act as the tower's primary structural core, supported by laminating and delaminating layers of walls as secondary structure.

After numerous quite different concepts, the final model was built using the robot to staple together paper strips at various positions. The resulting curved paper elements were used to produce the facades and the exterior corridors of the tower. The robot's ability to precisely staple connections in varying distances formed a synergy with the inherent material properties to enable complex geometric shapes. This project illustrates the robot's versatility to produce a wide variety of designs, and how to utilise the feedback loop between the physical model and the digital design. ▴



Sebastian Ernst, Sven Rickhoff, Silvan Strohbach and Martin Tessarz, *Prestudies to Undulating Terraces, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL), Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012*

The first iterations of towers were fabricated with simple picking and placing processes of modular components. In a second generation, material deformation was introduced, with custom-designed cardboard and aluminium bending processes.



Sebastian Ernst, Sven Rickhoff and Silvan Strohbach, *Undulating Terraces, Design of Robotic Fabricated High Rises, Architecture and Digital Fabrication, Future Cities Laboratory (FCL)*,

Singapore-ETH Centre for Global Environmental Sustainability (SEC), 2012  
One floor layer of the high-rise model showing the robotic stapled paper strips.

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