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Materializing hybridity in architecture: design to robotic production of multi-materiality in multiple scales

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ABSTRACT
Buildings consist of subsystems and components which have various functional and performance requirements. This inherent multiplicity demands the design and production of multi-material systems with varying and complementary properties and behaviours. This paper discusses a set of methods of digital design modelling and robotic production of hybridity in various architectural scales. In the case studies, the performance criteria serve as the underlying logic of the design and computation. The projects showcase how programmability and customizability of robotic manufacturing allow for establishing feedback loops from the production to design. Three projects are discussed in detail: a hybrid of flexible cork and rigid polystyrene, a hybrid of structural concrete with an intertwined permanent mould, and a hybrid of soft additively deposited silicone and subtractively produced hard foam. Each project has specific design performance criteria, with which a certain level of geometric complexity and variation is accomplished. Therefore, the research objective is to define and materialize the practical and robotically producible ranges of geometric complexities for each of the proposed methods. Additionally, the customization and development of robotic production setups are discussed. The research concludes that multi-materiality achieved through multimode robotic production methods introduces a higher, on-demand, and performance-driven resolution in building systems.

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Introduction

Buildings consist of subsystems, each with different requirements achieved by the assembly of multiple materials. In many contemporary practices in the construction industry, the sequential assembly of building elements, usually in multiple layers, results in the segregation of structure, finishing details, and other functional components. To provide alternative solutions for design to production of this inevitable multi-materiality, this research prototypes hybrid material systems that are produced with different robotic production methods. The presented case studies demonstrate and emphasize how robotically producible hybridity can improve different building performance indicators. Moreover, the projects elaborate on how these alternative materialization solutions require specific computational design and digital modelling approaches. Therefore there are three main scopes in this research: material hybridity, robotic production, and design computation. Considering the research scopes, the research proposition of this paper is framed based on the fact that there are discrepancies between methods of digital modelling and production of multi-materiality in existing design and building processes. Therefore, programmability and flexibility robotic means of manufacturing are exploited to provide customized methods of design to production for multi-materiality that are more coherent for architectural applications.

Surveying the state of the art projects, there are examples where the topic of multi-materiality is studied. In 'flow-based fabrication' numerically controlled composition of liquids create gradients of solidified materials which are additively deposited (Duro-Royo, Mogas-Soldevila, and Oxman 2015). In this example, as shown in the produced prototype, creating gradients in microscopic scales radically differ from the conventional layer by layer assembly of multiple materials, which is a dominating approach in building processes. Similarly, in this paper, materializing hybridity at architectural scales benefits from the customizability and programmability of robotic production setups in order to create multi-materiality in multiple scales. However, there is a fundamental difference between the presented cases studies in this paper and projects like the 'flow-based fabrication' in which the geometric and physical boundaries between the two or more materials are less distinguishable.

The ability to integrate multiple methods of robotic fabrication allows for the integration of multiple materials. Related to the body of this research, projects such as 'multimode production' methods (Mostafavi, Kemper, and Fischer 2018) in which two or more methods of fabrication processes are combined introducing potentialities of materializing hybridity. Further examples are 'wiggle wall', in which fast printing of foam is followed by robotic milling (McGee and Pigram 2011), 'Compound Fabrication' in which a subtractive routine follows an additive method for finer refinement of the surface quality (Keating and Oxman 2013), and a six-axis hybrid additive–subtractive manufacturing equipment with changeable head tools (Li, Haghighi, and Yang 2018). Next example in a larger scale is an all-purpose construction system with additive, subtractive, and assembling

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techniques which is proposed as Digital Construction Platform that utilizes a mobile system (Keating et al. 2014).

To produce hybrid material systems, in addition to the multi-mode nature of production techniques, methods of digital modelling and computation of multi-materiality are a fundamental aspect. With this respect, the process of translating a digital representation model into a production routine, which is customized for certain techniques, is studied in several projects. In Materially Informed Robotic Ceramic 3D Printing, a recursive system is developed through which a continuous robotic toolpath is computationally generated, in order to create a porous ceramic structure (Mostafavi and Bier 2016). Further computer-aided modelling methods, that facilitate the production of hybridity, propose voxel-based representation techniques for complex material distributions (Michalatos and Payne 2016). The voxel-based modelling approaches allow for a higher resolution application of additive manufacturing. While using robotic manufacturing at architectural scales, further compound digital modelling approaches are required in which the nature of robotic tooling is considered. Therefore production routines provide feedback to design materialization processes and digital modelling approaches. This integration of fabrication constraints within the architectural design process creates the possibility for direct and instantaneous feedback between the fabrication constraints and the design intent (Pigram and McGee 2011). Consequently, the case studies in this paper present a framework of design computation to robotic production methodology with the focus on multi-materiality in various architectural scales. The three projects discussed in detail are: hybrid of flexible cork with rigid polystyrene, hybrid of structural concrete with permanent parts of the mould intertwined, and a hybrid of soft additively deposited silicone with subtractively produced hard polystyrene. The third case study is explained in more detail as a conclusive project on design to the robotic materialization of hybridity.

Case studies: design to robotic production of hybridity

Each of the prototypes presented in this paper are a part of a larger design project with specific structural, functional, and environmental architectural performance criteria. While performance criteria are discussed briefly, the focus in descriptions of case studies is mainly on multi-materiality in relation to methods of robotic production. The hybridity is explained from three perspectives: the physical and architectural properties of the hybrid material systems; feedback loops from robotic production informing the design materialization processes; and methods of computer-aided modelling, digital representation, and computation of multi-materiality. The objective, on the one hand, is to construct applicable building systems that are informed by specific architectural performance parameters, and on the other hand, is to develop and test customized design to robotic production processes.

Hybrid cork

Figure 1. Hybrid cork.

The hybrid of flexible porous cork and hard polystyrene showcases a one-to-one prototype, which is a vertical section part of an indoor stage structure with sound absorption capacities (Figure 1). The project focuses on the integration of two different materials by using two distinct methods of subtractive robotic manufacturing. The materials used are rigid cork boards, with a thickness of 30 mm, and blocks of high-density Expanded Polystyrene (EPS). In the underlying design proposal, the distribution of robotically treated cork is informed according to areas either requiring comfortable seating surfaces or sound absorptive properties. The thickness variation and porosity of the EPS components are computed according to any structural and functional requirements, such as light and sound absorptive qualities and solidity for the constructive framework of the stage. Sound reflection analyses inform the overall topology, as well as the distribution of cavities between the two materials.

The three-dimensional robotic treatment of the cork boards allows for the adaption and controlling of the physical material behaviour of the cork boards and consequently creates a hybrid system from the two different materials. The change in bending behaviour is achieved through introducing three-dimensional notches on both sides the cork boards. The varying depth and width of the milled pattern on the cork boards results in a double-curved surface, which fits onto the allocated areas of the pre-milled EPS structure. The semi-closed double-curved porous cork allows the sound waves to penetrate the structure, while the hard closed EPS valleys lock the waves into the cavity until they abate (Figure 2).

A key factor in this project is the feedback loop between the digital simulation of surface unrolling routine, using Kangaroo Physics Solver in Grasshopper plugin in Rhinoceros®, and the robotic production of the actual cork board with thickness. The unrolling process is evaluated and adjusted through a series of digital simulations and physical prototypes with different milling patterns. Although the digital simulation provides an initial guideline for the unrolling strategy, a series of prototyping is necessary to understand the actual bending behaviour of

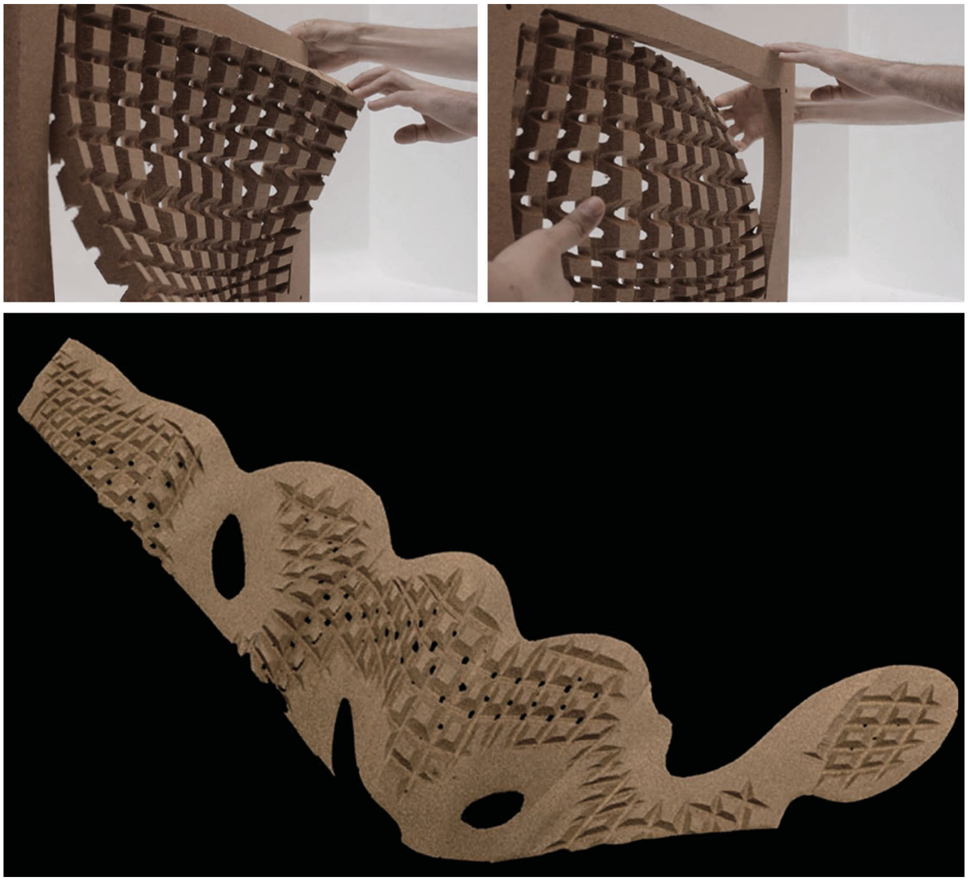


Figure 2. Cork gains intended flexibility and double-curved bending.

different carved out patterns on solid materials. This is mainly due to the level of detail and abstraction in the simulation model. The simulation process is based on a simplified surface version of the solid cork boards that provides a rough approximation of the unrolling process. Therefore, considering the fact that a bending process with actual thickness in a mesh format is not feasible or it is a computationally heavy process, the series robotically produced prototype is playing a complementary role to fine tune the dimensions and determine the geometry of the removal pattern on the cork.

While the first milling operation on EPS follows a common perpendicular layer-by-layer roughing routine, the second subtractive process on the cork is applied differently, where ruled surfaces are guided on the notches (Figure 3). In order to achieve the intended bending behaviour, notches of material are peeled off from both sides of the rigid cork boards. The achieved multi-directional flexibility of the cork matches the target curvature of the design. In the assembly process, the two-dimensional cork panels are mapped onto the three-dimensional EPS components, then deformed and attached on the intended contact areas (Figure 1). Consequently, the produced prototype demonstrates a built-in hybrid behaviour. This means that in certain areas the cork elements are rigid and in other areas, they have gained the intended elasticity through the robotically produced notches. Therefore, the cork is flexible where it is not fully supported by the second material and it is stiff in areas where the two materials perfectly overlap.

Hybrid concrete

The hybrid of concrete intertwined with permanent parts of the mould is a multi-material system with concrete as the structure and EPS as the second functional material (Figure 4). Unlike the common two-sided mould for casting, the mould for this cast consists out of four robotically produced components. Therefore, certain EPS parts are functioning as temporary casting mould elements, while some other permanent parts are intertwined with concrete to act as insulation and finishing. The prototype is extracted from a building skin that is designed according to structural and environmental analyses. The result of these analyses is an information point cloud with values extracted from stress analysis and environmental simulation. The distribution of the structure in this discrete point cloud originates from a topology optimization routine while the distribution of the second material is controlled according to other functional and environmental factors. Beyond the architectural design considerations, the main research objective is to robotically produce a hybrid system in which the two material are integrated. As a result, both materials are designed and computed as closed meshes or volumetric continuous topologies, which are interlocked together three-dimensionally.

Considering the physical properties of both concrete and EPS, the minimum to maximum dimensions and variations in thickness are defined with a series of initial prototypes. From a point of view of digital modelling of a hybrid system, this

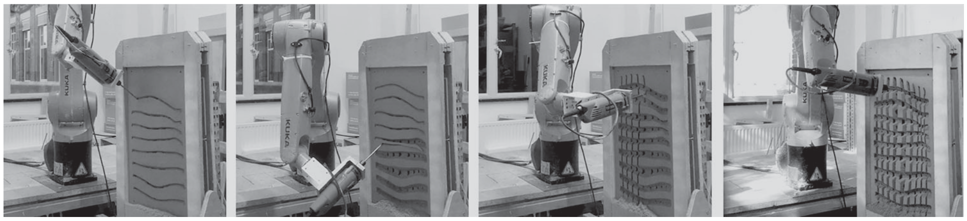


Figure 3. Multi-directional carving out notches from rigid cork boards.

Figure 4. Hybrid concrete.

project presents challenges with respect to the translation of voxelized or discretized results of material computation into producible geometries, and eventually robotic toolpath generation. Moreover, the design is rationalized according to the reachabilities and collisions in the robotic tooling process. This implies avoiding unreachable overhangs on the finishing surface of the mould. The core finding, from a geometric point of view in this study, is to model the overall topology of the component according to a middle surface. As a result, both concrete and EPS surfaces, which are generated based on the point cloud, are then rationalized according to an offset from the middle surface. This rationalization, on the one hand, assures that each part of the mould is robotically producible, and on the other hand guarantees that the two remaining parts of the mould will stay in place without the use of any glue.

The first prototype is casted in concrete only (Figure 5). This iteration is to determine the ranges of producible dimensions of fibre reinforced concrete to be casted in a two-part formwork. In this prototype, the method of production and parametric toolpath generation with KUKA|prc in Rhinoceros® Grasshopper 3D is tested and verified (Figure 6). In the second prototype, unlike a common two-sided mould for casting, the mould consists of four robotically produced elements.

Figure 5. Concrete branch test sample, with robotically produced mound with two temporary mould parts.

A four-part formwork is produced as the final hybrid concrete prototype. Out of these four elements, two are closer to the concrete core and remain in place after stripping the formwork (Figure 7). Two outer EPS blocks partially removed, and the side boundary surfaces of the overall hybrid component are designed as developable surfaces and produced with hot wire cutting routines. The finished surface is mainly EPS as protection or insulation with a softer texture, and exposed harden concrete parts which extrude out from the EPS surface in certain areas. The range of diameters of the concrete branch varies from 22 to 65 mm. The thickness of the EPS ranges from 8 to over 300 mm. The sizes of the openings, or the porosity integrated into the component, range from 20 to around 200 mm. The permanent EPS elements stay interlocked in place without the use of glue. This is due to the three-dimensionality of the concrete structure that keeps the two EPS elements securely in place (Figure 8).

Hybrid silicone

In the hybrid silicone project, a multimode subtractive–additive robotic production method is implemented. Three different robotic subtractive routines, such as hot wire cutting, milling for rouging and milling for finishing, followed by one additive material deposition procedures are combined into one setup. Merging multiple robotic manufacturing methods results in a multi-material system, consisting of subtractively produced hard polystyrene and additively deposited soft silicone (Figure 9). The

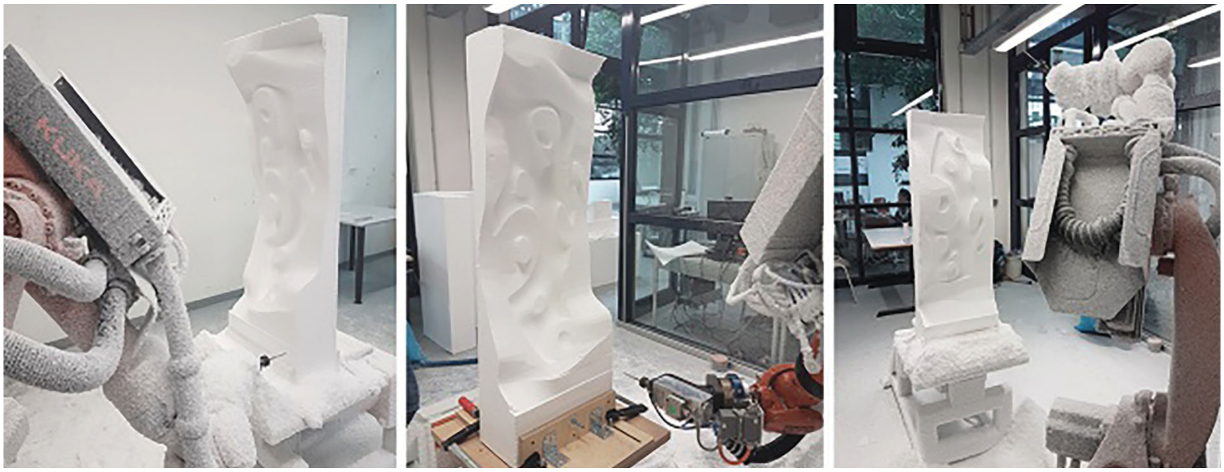


Figure 6. Milling process of the test mould for concrete casting with two parts.

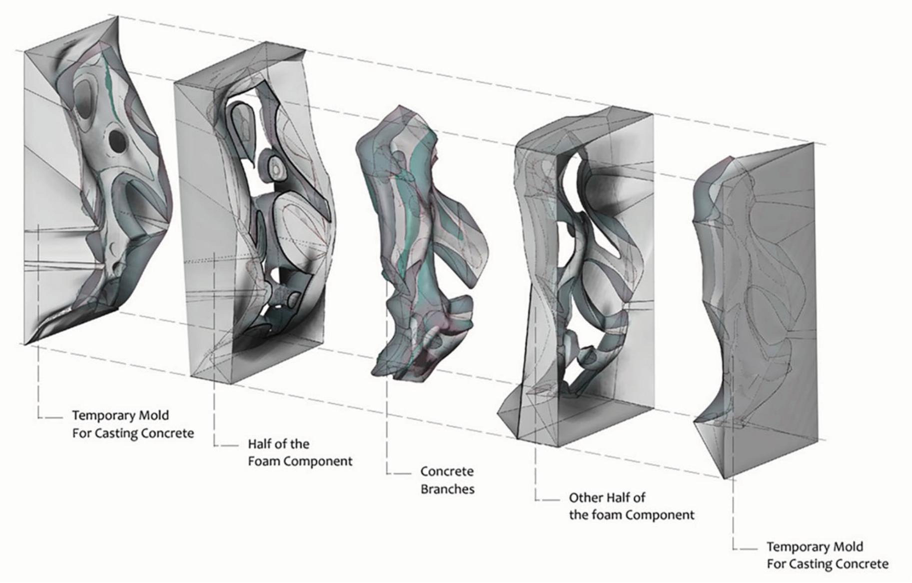


Figure 7. Mould of hybrid concrete prototype with four robotically produced parts.

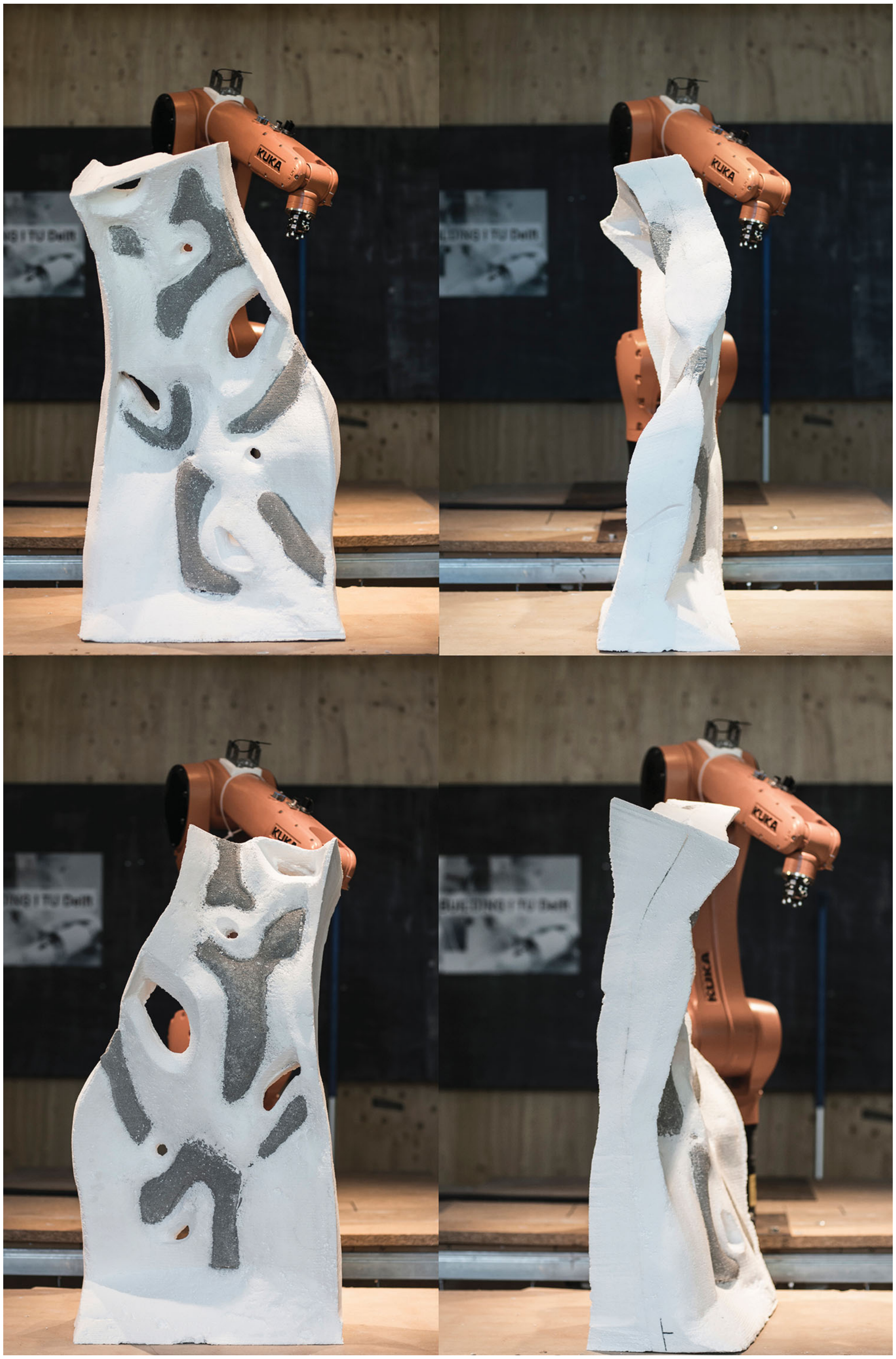


Figure 8. Different views of hybrid concrete prototype.

research evolves along a set of experiments involving material behaviour, in order to develop an additive production method for the viscous silicone. From a design perspective, the aim is to model and compute the density and distribution of silicone as a soft material combined with the hard polystyrene. Consequently, in the presented case study, the goal is to benefit from the elastic performance of the printed geometries for specific surface qualities and functions.

Subtractive–additive

In addition to the background research on multimode robotic production mentioned in the introduction, there are related projects that employ a combination of subtractive and additive production methods. The 'Woven Clay' project uses temporarily milled foam as an undulating printing bed where the clay paste is deposited from a distance above the surface (Friedman, Kim, and Mesa 2014). A similar combination of subtractive and additive

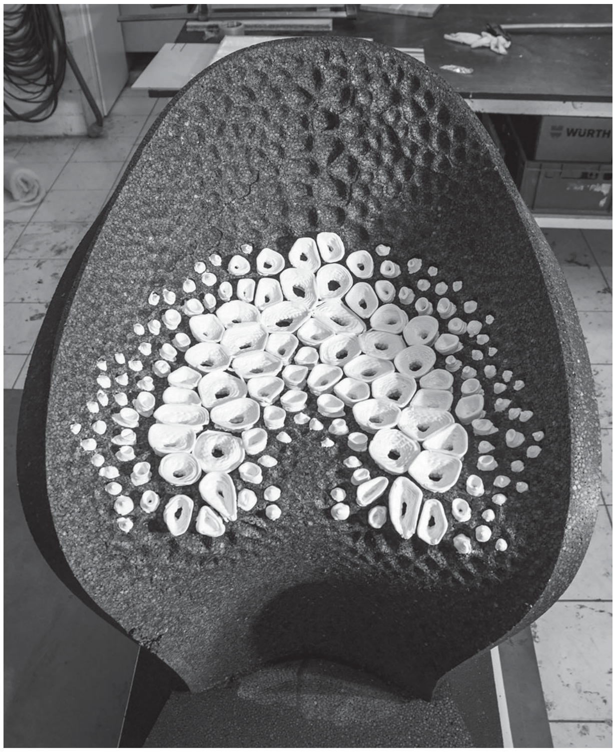


Figure 9. Hybrid chair produced with hybrid silicon method.

manufacturing methods is tested in the 'materially informed 3D printing' project where the deposition toolpath fully follows the surface geometry of the component, which is produced with robotic hot wire cutting (Mostafavi et al. 2015) (Figure 10). In most of the additive production processes such as Fused Deposition Methods, Selective Laser Sintering, Stereolithography, or conventional casting, the physical state of the material changes from one state to another. The phase change does not allow for simultaneous or sequential integration of two processes of subtractive and additive manufacturing. The hybrid project presented in this paper uses silicone as an adhesive material that it is able to permanently stay in place. The chemical curing process of silicone does not require heat or a different source of energy for solidification. These material properties enable an affordable additive manufacturing system that can be combined with a subtractive method for architectural scale applications.

In order to combine subtractive and additive production methods, series of silicone robotic 3D printing experiments are tested on double-curved and freeform surfaces. In summary, two main conclusions are derived from the outcomes of these experiments, which are described in detail in the following sections. The first conclusion set is documented as a set of fabrication rules and material constraints and potentialities. The second set of factors are related to geometric aspects such as microscale details in the robotic toolpath design or the ranges of printing angles where no support structure is required.

The elasticity of various shapes with different thicknesses is studied, documented, and evaluated for potential design applications. With these objectives, a customized extruder for silicone printing is designed. Exploiting the movement ability of a robotic six-axis arm, the extruder with two changeable material containers, i.e. translucent and opaque silicone is located on top of axis three of a KUKA Agilus KR 10 robotic arm. Therefore the specific design of the extruder allows for a short connection to the nozzle, directly on the tip of axis six. Between the calibrated tip of the tool and the flange, a ball bearing is integrated that allows for free rotation of the slender funnel. Consequently, the connecting pipes from the cartridges to the nozzle face upwards during the movement. This short tube connection enables higher ranges of three-dimensional movement of the nozzle on complex surfaces (Figure 11).

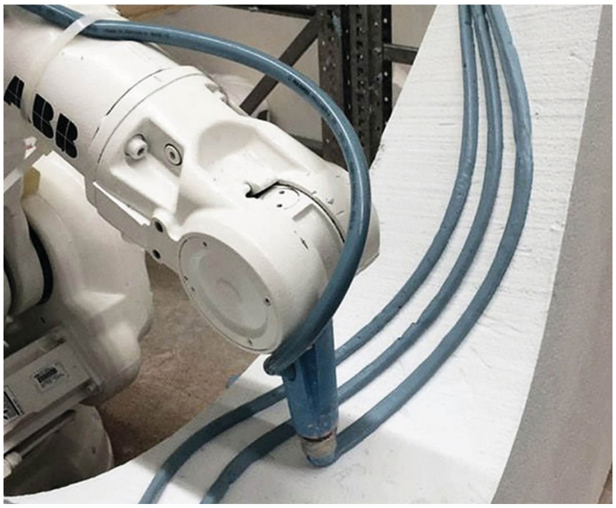


Figure 10. Robotic 3D printing on a freeform surface.

Two main categories of cellular and linear silicone robotic toolpath and ranges in between are tested. Findings of the experiments in detail are:

(1) Linear printing on double-curved fabric with a continuous toolpath using an external fixed extruder (Figure 12, top): This resulted in determining first workable values considering the speed of the robot, the material flow, the vertical distances between layers, clarification of the silicone properties, pot life, curing time, and viscosity.
(2) Flat cellular printing on double-curved fabric results in extruder modification (Figure 12, middle): This concluded in reducing the distance between the external extruder and the printing fabric, which results in a shorter tubing system. A custom build extruding system is mounted on top of the robot to provide the shortest length of tubes possible.
(3) Medium to large size cellular printing on flat fabric with five types of toolpath with the mounted extruder on the manipulator. Conclusions are diameter and height ranges of the printed cells: $25\,\text{mm} < D < 105\,\text{mm}$ and $11\,\text{mm} < H < 125\,\text{mm}$ (Figure 12, bottom). This iteration is feedback for the estimation of the maximum angle for cantilever printing, heights, and wall thicknesses. This experiment results in sufficient printing quality of medium to large cell shapes and the verification of the previous tested specific printing values.

Based on these experiments, the overall printing quality is improved. The opening of the tapered nozzle is set to a diameter of 3 mm. For a consistent connection between two extruded

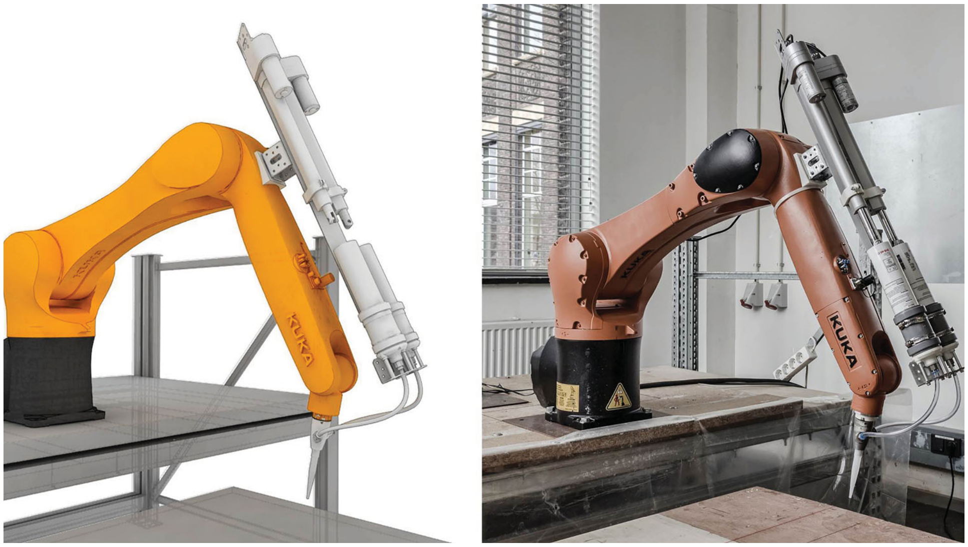


Figure 11. Parametric simulation with in KUKA|prc with integrated digital model of the extruder (left); robotic additive manufacturing setup for silicone printing with KR10-1100 (right).

Figure 12. Robotic silicone printing experiments, linear continuous printing (top); cellular printing on a free from fabric (middle); prototype testing height, cantilevering and size ranges (bottom).

layers 0.6 mm of overlap is required, which results in a 2.4 mm printing layer height. The maximum printing angle can exceed 45 degrees. The angle correlates with the following factors: viscosity, wall thickness, the stickiness of the silicone type, overall topology, and the mass of material to be printed on top. Therefore, an exact value is always specific to a certain shape and size. As seen in iteration three, the material and printing method has the potential to print cantilevered parts. The printed silicone reacts with air after extrusion, and the curing process begins within 15 min. Fully hardened silicone can be welded together with fresh silicone. These attributes allow for taller prints with maximum cantilevering angles.

To test and evaluate the proposed multimode robotic production method, a proof of concept prototype with black polystyrene hard foam and silicone is produced (Figure 13). The hardened outcome of the printed cells demonstrates the desired elastic behaviour while it firmly stays glued to the foam. Further tests are also conducted where, through the introduction of a sine wave in the toolpath, the contact area of the two materials as well as the printing layers is effectively increased

Figure 13. A test sample as a proof of concept prototype integrating subtractive robotic manufacturing applied on EPS and additive deposition of silicone with robotic arm.

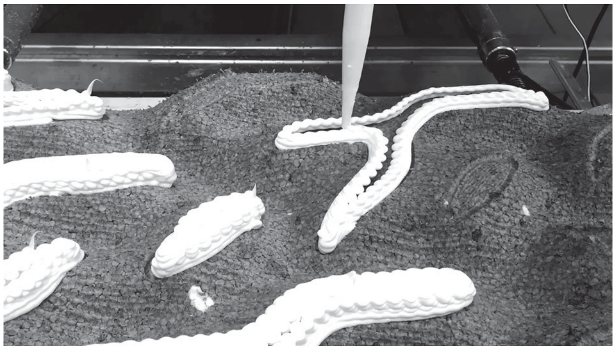


Figure 14. Fortifying sine wave toolpath for silicone printing to increase the stability of printed material.

(Figure 14). This microscale manipulation results in an efficient material deposition method.

Design to fabrication workflow and prototyping of the hybrid chair

The workflow is extended and demonstrated in the design-to-fabrication process of a prototype hybrid chair (Figure 15). This process considers the key topics discussed with regards to subtractive production in combination with the opportunities of silicone robotic 3D printing. The integrated workflow establishes interconnected feedback loops between digital modelling, design computation, material properties, and a multi-mode robotic production method. The project proposes a hybrid system composed of high-density polystyrene, as a hard material, and silicone, as soft material. The macro-scale geometry of the chair is designed in foam with developable surfaces. In microscale, a distribution pattern in relation to the contact areas of the human body to the seating surface is applied.

The form-finding to design materialization methodology of the hybrid chair includes three main feedback loops from the multimode robotic fabrication (Figure 15). As these three processes are considered and simulated in one seven-axis setup (KR 240-2 150): six-axis robotic arm with a linear rail, it is essential to iteratively evaluate the constructability of the design by examining the overlaps between the optimum production space of each method. The distribution of the silicone cells with differentiated sizes and typologies is implemented according to the contact areas with the human body as it pertains to the seating and weight distribution on the front side of the chair. In similar scales, multi-materiality is explored and tested in chair design projects. Among them are the Gemini chaise (Oxman et al. 2014) with a focus on acoustical performance and the multicoloured multi-material ZHA chair (Bhooshan, Fuchs, and Bhooshan 2017) with an emphasis on structural efficiency gained through multi-material printing in a layer-by-layer fashion with high resolution. In the hybrid chair project, flexible material with a feasible resolution for silicone printing is considered to be robotically deposited directly on the subtractively produced volume with three-dimensional surface tectonics.

The macro-scale design is an iterative exercise implemented with Autodesk T-Splines in Rhinoceros 3D. The output of this modelling process is a digital model, which is then rationalized to four continuous developable surfaces that approximate the design (Figure 16(a,b)). The result of this approximation is then translated into an initial parametric model, which is linked to the robotic production simulation that allows for minor parametric customization of the design in macro-scale. To decreasing the volume weight of the chair an internal hole with an adjustable three-dimensional twist is introduced. The seating area pattern and the additive silicone cells, as well as all robotic production routines, are compiled in one script. This integration ensures an unbroken design to the production chain.

The next mode of production is robotic milling on only the concave curvature of the front face of the hybrid chair (Figure 17). While the macro design shape is produced by hot wire cutting, milling is used to shape the seating area further. Roughing is necessary and only applied in this area to accelerate the process. The robotic milling toolpath follows the cellular

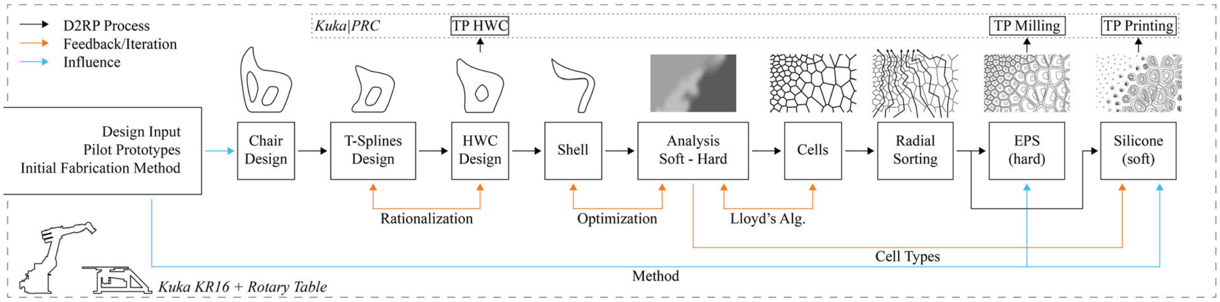
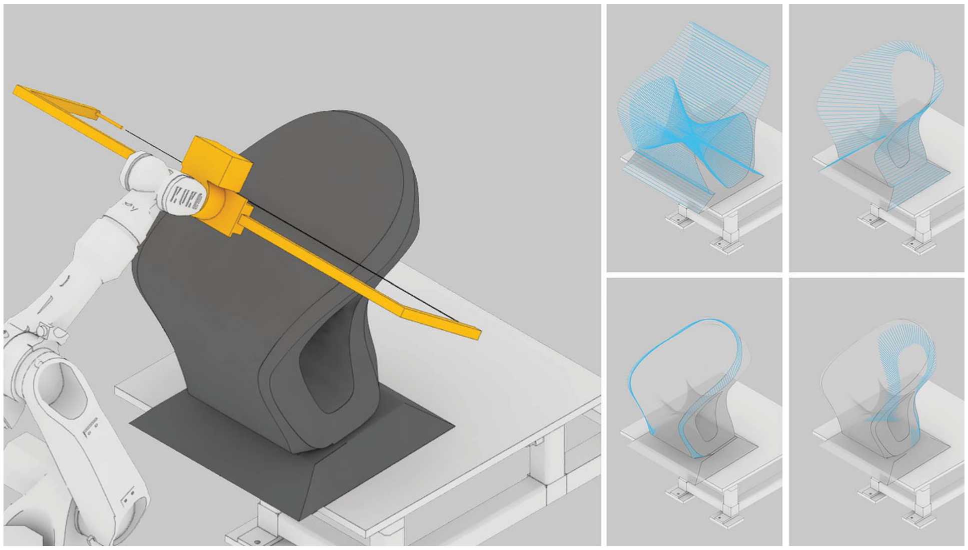


Figure 15. Hybrid chair design-fabrication flowchart with rationalization and optimization feedback loops.



(a)

(b)

Figure 16. (a) Robotic hot wire cutting of overall form, with only four cuts out of which one side will be milled for more elaborated and required details. (b) Hot wire cutting the developed surfaces of the hybrid chair.

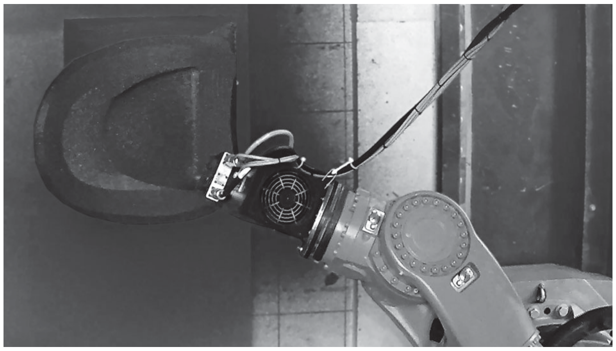
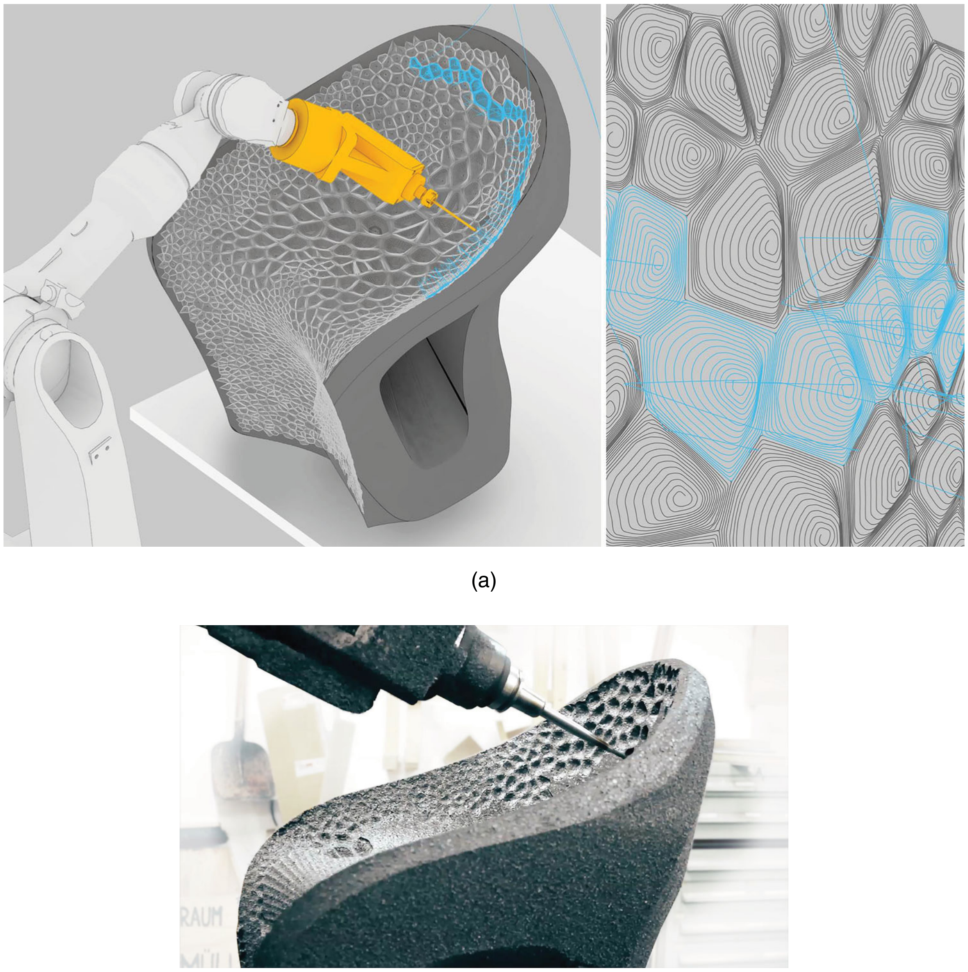


Figure 17. Concave curvature surface robotic milling of the hybrid chair.

logic of the front surface that varies in size and depth according to the distribution of the soft silicone cells. To stay as perpendicular as possible to the surface during the milling process, the toolpath is parametrically generated based on the original cellular logic of the geometry. Each cell has a local enter and exit safe point above the surface which is followed by radial incremental material removal. In this process, instead of conventional layer-by-layer material removal, the milling follows the cellular and thus a radial logic (Figure 18(a,b)).

These two subtractive processes are followed by an additive method. Silicone cells with varied sizes, depth, and typologies are distributed on top of the three-dimensional concave front milled surface of the chair (Figure 19(a–c)). The printability of the cells is decided based on a series of experiments on the fabric as well as the tests on EPS. The toolpath generation follows a similar cellular logic applied in robotic milling from the previous step. In this process, the continuity of the printing path is essential. Continuity in this stage of production means that after finishing the printing of one cell, the toolpath always continues to print an adjacent cell and avoids hovering above the surface until all cells are produced.

An optimized robotic milling toolpath reduces the production time of high-resolution milling and printing. Due to the difference in the number of neighbouring cells and the size gradient, a one-directional sorting technique is not applicable. The nature of cell distribution on the hybrid chair demands a tailored sorting approach that results in a continuous sorting with short travel time. Therefore, the outer edge of the chair shell is considered as a reference for a radial sorting from outside



(a)

(b)

Figure 18. (a) Simulation of robotic milling on the concave part of the hybrid chair (left); incremental radial material removal strategy to fabricate the cellular pattern (right). (b) Process of milling the cell in higher resolution perpendicular to the geometry that results in a refined surface quality and increases the friction between two materials.

to inside (Figure 20). Since both subtractive and additive processes are executed in one setup, it is essential to inform the design through robotic simulation of both processes. As each of these processes has different optimum workable production space, it is important to know the overlap between these optima.

Conclusion

The methods of design to robotic production of hybridity presented in this paper explore interrelations between different design scales, multiple fabrication methods, and various building materials. The approaches specifically define architectural robotics as a field of feedback and feedforward routines between three key research domains: computation, automation, and materialization. Focusing on multi-materiality, each of the three prototypical case studies in this paper highlight certain challenges with regard to each of these domains; summarized in the conclusion table (Table 1). According to the description of the case studies, as well as the comparison provided in the table, the following conclusive points and future directions can be discussed.

Materializing multi-materiality in architecture using robotic manufacturing requires the custom design to robotic production models and workflows. An applicable and coherent model facilitates the design and production of porosity, hybridity, and assembly, as three essential operational design materialization components (Mostafavi and Anton 2018). Starting from application-based research, which evolved towards concepts and methodologies for robotic implementation, the studies show how novel material architectures can be conceived and produced. In this context, material architecture refers to a new multi-scalar system that ranges from micro to macro according to the inherent constraints and potentialities of innovative production methods. The proposed innovation is dependent on how computation, automation, and materialization are formulated and integrated. Eventually, the outcomes of these customized processes facilitate the construction of efficient building products with multiple materials. The achievable hybridity expands the physical property-space of materials that are producible – and therefore implementable – in design.

The design space is characterized and informed with the method of robotic production through a set of feedback that implies customized methods of digital modelling, representation,

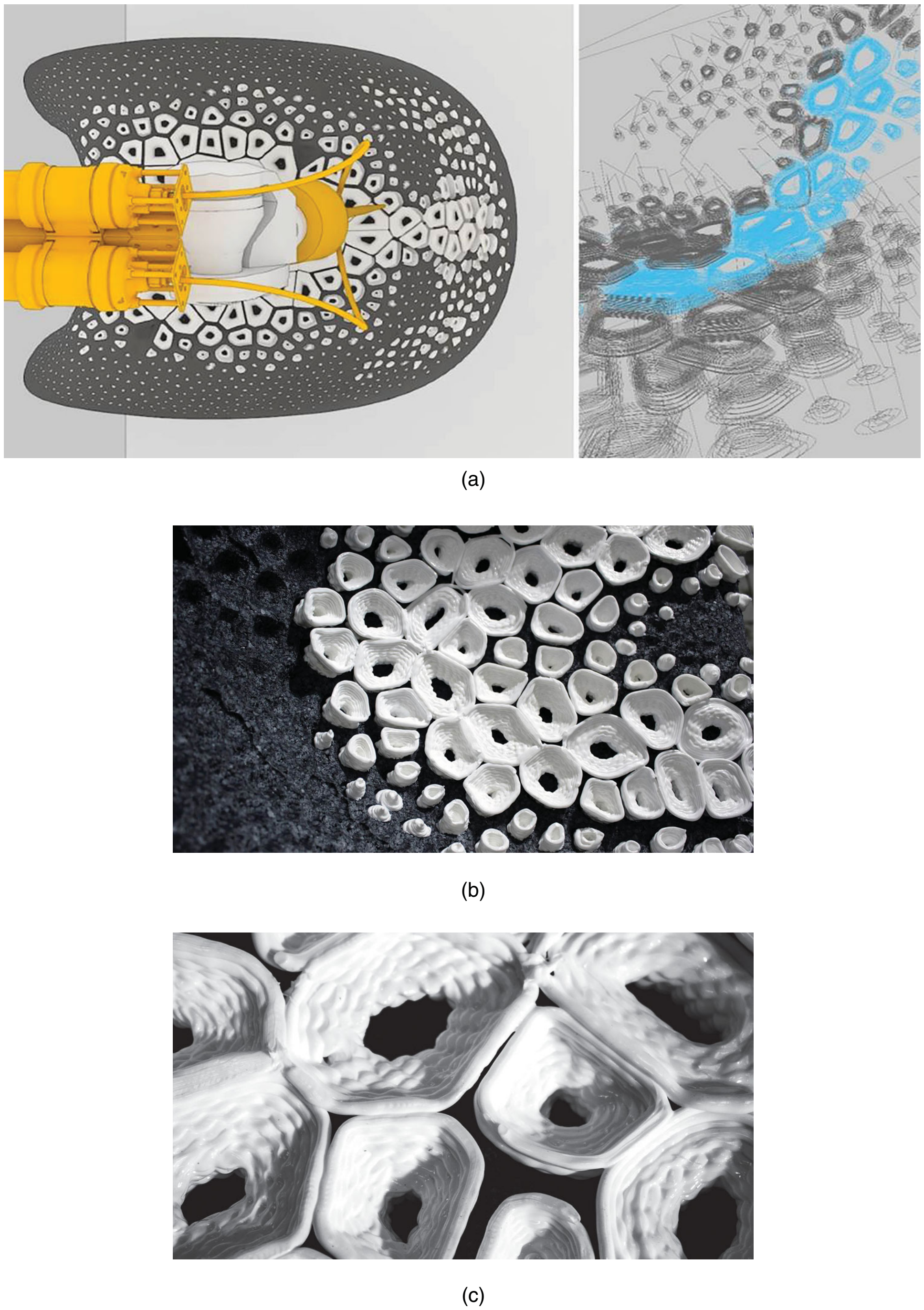


Figure 19. (a) Robotic 3D printing of silicon on subtractively produced front concave surface of the hybrid chair (left); continuous printing toolpath (right). (b) Silicone cell on EPS surface, a zoom in view of the hybrid chair. (c) Silicone cell on EPS surface, the fortifying sine waves smoothly disappear as the print reaches the tip of cantilever.

and computation. Consequently, in addition to dominant surface based and boundary representation modelling methods, alternative modes of volumetric, curve-based, and more fabrication methods of computer-aided design are needed. These alternative modes of modelling to production are introducing volumetric approaches to design, which are implementable through both subtractive and additive processes of manufacturing, such as hot wire cutting, milling, and printing. In these processes, in order to develop an operational design materialization method, simulation and computation of the tooling process are essential, through which the sequences and combination of multiple techniques are controlled.

Being able to design and customize different types of end-effectors to be integrated into a robotic production setup introduces gradients of varying material handling and processing approaches for building applications. With a focus on subtractive and additive approaches, the case studies in this paper provide a set of prototypical projects on multimode robotic production and a concluding design-to-prototyping process of the hybrid chair. The projects emphasize how the process of design materialization is influenced by the established feedback loops of robotic fabrication, and how both subtractive and additive methods combined are approached or customized differently for more effective production systems. Moreover, the efficiency

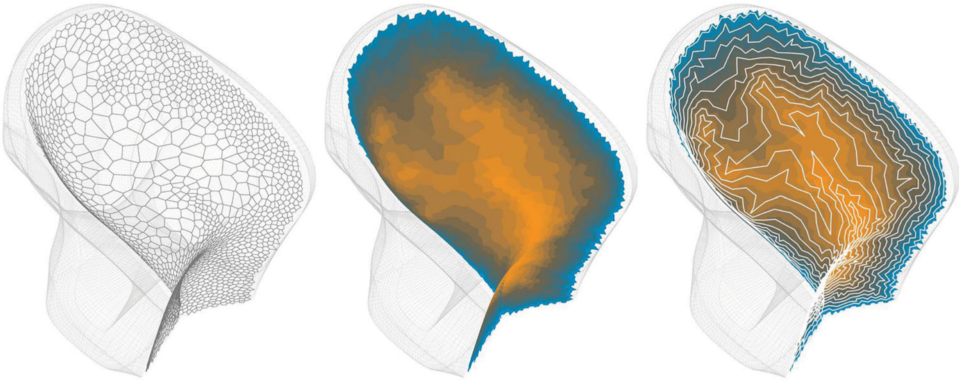


Figure 20. Resulting cell distribution after human body analysis (left); toolpath optimization following a radial logic (middle); continuous toolpath travels through all cells without hovering above the surface (right).

Table 1. Multi-materiality, robotic production, modelling and computation, geometry and performances of the hybrid projects summarized and compared.

		Project		
Subject		Hybrid cork	Hybrid concrete	Hybrid silicone
Multi-materiality		• Hybrid of hard Expanded Polystyrene with flexible cork • Raw materials: EPS volumetric blocks and rigid cork boards	• Hybrid of hard Expanded Polystyrene with reinforced concrete • Raw materials: EPS volumetric blocks and concrete mixture	• Hybrid of hard Expanded Polystyrene with elastic solidified silicone • Raw materials: EPS volumetric blocks and liquid silicone mixture
Robotic and production		• Two processes: robotic milling and robotic carving • Volumetric subtractive manufacturing on EPS and multi-directional carving out notches from rigid cork boards • Assembly of the bendable cork interlocked in place on milled EPS	• Two processes: robotic milling, casting followed by robotic hot wire cutting • Volumetric subtractive manufacturing and casting the mixture • Two permanent parts of the EPS mould are assembled together without glue as they are intertwined with concrete	• Three processes: robotic hot wire cutting, robotic milling and robotic 3D printing • Multimode of subtractive – subtractive – additive, roughing is applied only on the concave surface • Assembly of printed cells directly on the surface controlled with a higher resolution milling in contact areas and the adhesive properties of silicone
Modelling and computation		• Modelling the details of the pattern directly with controlling the angles in robotic milling toolpath • Simulation as guideline for unrolling three-dimensional cork into flattened surfaces using a physics engine	• Modelling the component according to a middle guiding surface that all of its boundary surfaces are generated as an offset of this guiding surface • Topology optimization of structure and translating the discrete point cloud into producible meshes	• Procedural modelling workflow with feedback from multimode robotic fabrication and toolpath optimization • Modelling the geometry of silicone cells with toolpath represented as curve • Computed continuous toolpath for milling and printing that includes all cells, avoids collisions and minimizes the total hovering travelling time
Design	Geometry	• Volume + Surface: volumetric component with thickness variation interlocked with thickened surface with multi-directional pattern that integrates porosity and varied notches	• Volume + Volume: volumetric concrete element with varied diameters of branches intertwined with volumetric EPS elements that are both topologically continues volumes	• Volume + Curve: Volumetric EPS element designed with rationalized developable surfaces and mesh geometry of the concave seating area with continuous curves that are representing the cells
	Performance	Acoustic and surface quality	Structural and functional requirements	Comfort in seating area and surface quality

of the produced building systems is improved with the potential of higher resolution and multi-material architecture facilitated by multimode robotic production methods. The new resolution, which is multi-scalar in nature and concerns simultaneous design to production in multiple scales, ranges from micro to macro.

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