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The Architecture of Slicing

Balancing Automation, Design and Sustainability in Digitally Fabricated Concrete Through RHWC

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Digitally empowered tools and processes for making, such as robotic fabrication and 3D printing have enabled the materialization of designs of ever-growing complexity, with the promise of unprecedented expressive freedom but also with the promise of automation and its economic benefits. Simultaneously, controlling new digital processes also presents opportunities to address the need for a more socially responsible and sustainable architectural practice. What is not clear is how such technologies can be critically appropriated in architecture, balancing all these solicitations.

This paper centres on a digital fabrication tool for concrete architecture – robotic hot wire cutting. It focuses on the emerging opportunities of the mechanics of slicing, and proposes to answer the question: How can digital fabrication tools balance the allure of automation, the responsibility of sustainability and the drive for artistic production? *To answer this question, we present a thematic analysis of these issues, based on the combination of the findings from a set of four experimental prototypes developed to explore these issues.*

1 Digital Concrete Construction

In the field of digitally empowered architecture, the case of concrete is increasingly relevant. On one hand, concrete is the most widespread construction material in the human landscape and demand for it has shown no signs of decreasing. Unfortunately, it is also a material which is renowned for its heavy carbon footprint. The large volume of Portland cement required for concrete construction makes the cement industry a large emitter of CO_2 responsible for about 5% of annual global anthropogenic CO_2 emissions.[1]

On the other hand, concrete has a rich, multi-faceted tradition in architectural history. Its ability to be moulded into almost any shape including complex free forms, express different textural effects and assume different material qualities are important material features of concrete, and are at the centre of its architectural appeal. Nevertheless, they are all linked to a complex, material and labour-intensive construction process, which at times has imposed technological, economic and material limitations on concrete architecture. In turn, since the advent of the industrial revolution, there have been efforts to achieve some degree of automatization and systematization of concrete construction processes, as potential solutions to its inherent difficulties, particularly in the production of formwork. This path, in conjunction with rising labour costs in the second half of the 20th century, led to the increase of standardized architectural solutions with limitations in design geometries and the proliferation of the precast industry.

Advancements in digital design and, particularly, digital fabrication technologies have rekindled the possibility for the design of a more expressive concrete architecture, backed by the potential of these tools to do away with economies of scale which propelled standardization, enabling the creation of customized designs by means of digitally automated processes.

In the field of digital fabrication, the landscape of technologies and strategies for materializing concrete has changed substantially in the last two decades, from the initial CNC (computer numeric control) milling of formwork, which allowed for increases in formal freedom, automation and precision, to the more recent processes for the direct 3D printing of concrete elements, which entirely bypass the use of formwork systems.[2]

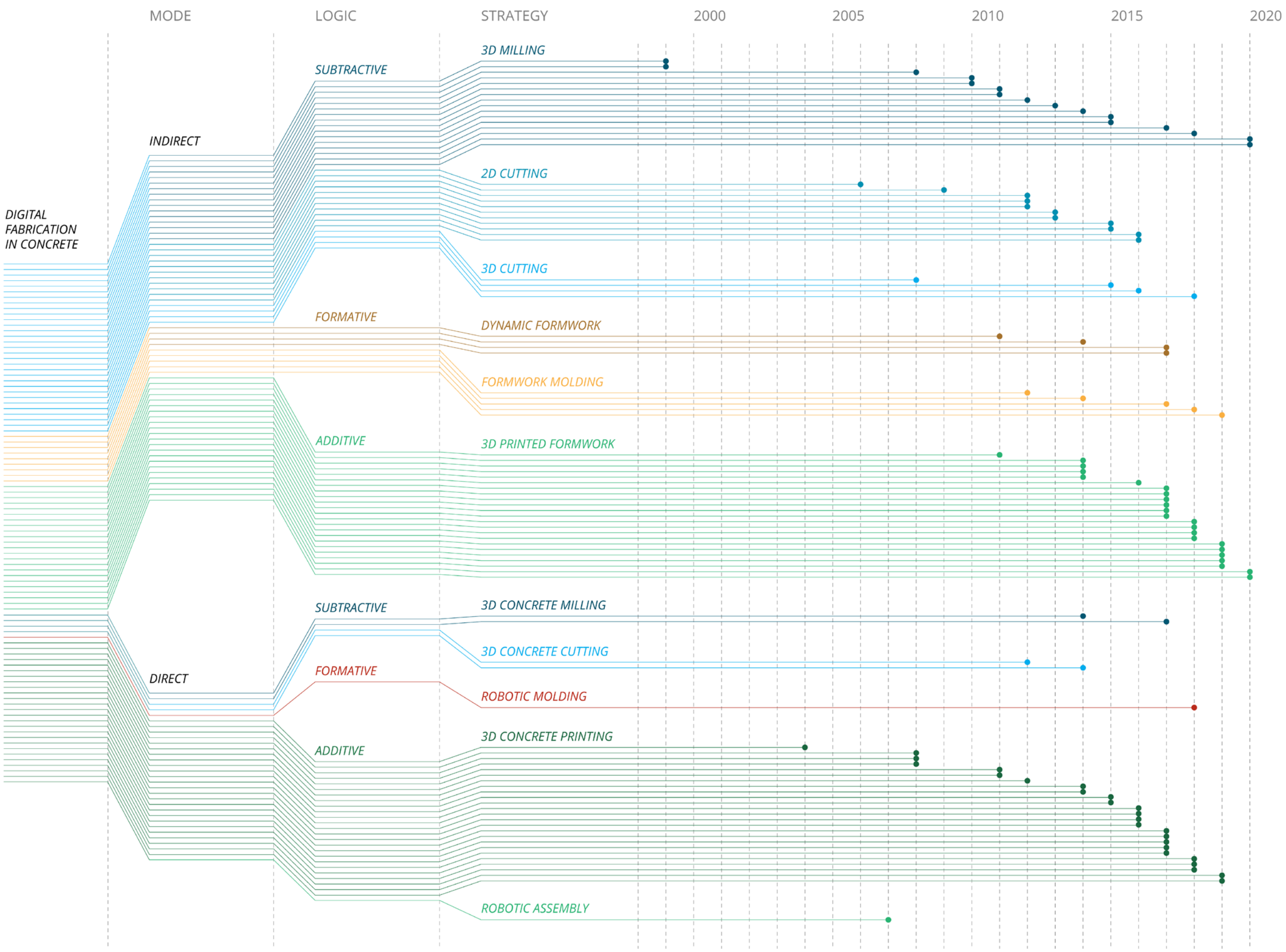
Although traditional concrete building technologies strategies still prevail, some digital processes have already been adopted into the construction industry, but many are also being developed through academic research. Independently of this status, today there are distinct digital fabrication processes which have the potential to provide different approaches to making concrete elements. This expanding landscape of digital concrete making naturally leads a multitude of construction strategies, all with particular sets of inherent benefits and constraints, but also design logics, linked to specific technological tools.

1 Jos G.J. Olivier, Jeroen. A. Peters, and Greet Janssens-Maenhout, "Trends in global CO_2 emissions," report (2012). https://www.pbl.nl/en/publications/trends-in-global-co2-emissions-2012-report

2 Alan Dempsey, "From parameter to production," *Advances in Architectural Geometry 2008*, Conference proceedings (Vienna: AAG 2008, 2008), 87-89; Sungwoo Lim, Richard Buswell, Philip Valentine, Daniel Piker, Simon Austin, and Xavier De Kestelier, "Modelling curved-layered printing paths for fabricating large-scale construction components," *Additive Manufacturing* 12 (2016): 216–230.

Fig. 1 Classification and timeline of different examples of digital fabrication strategies for concrete elements, using three parameters: intervention mode, transformation logic and technological strategy (developed by the authors).

Figure 1 presents an overview of this landscape with approximately 100 examples of built works and academic prototypes in concrete developed in the last 20 years, illustrating the expansion of digital fabrication processes for concrete architecture. They are subdivided into two main typological distinctions, considering the use or avoidance of formwork. These are further divided into 11 different strategies, considering the specific technological and material transformation process, resulting in: a) indirect digital fabrication processes to *carve (3D milling), cut (2D cutting), slice (3D cutting), mould (dynamic formwork; formwork moulding) and 3D print* formwork and b) direct digital fabrication processes to *carve (3D concrete*



3 Peter Jones and Eric Simons, *Story of the Saw* (Schefield: Spear & Jackson Limited, 1961); Anna Smogorzewska, "Technological Marks On Pottery Vessels. Study Of Evidence From Tell Arbid, Tell Rad Shaqrah And Tell Jassa E-Gharbi (Northeastern Syria)," *Polish archaeology in the Mediterranean*, XIX (2010): 555–564.

milling), cut (2D concrete cutting), mould (robotic concrete moulding), assemble (robotic assembly) and 3D print concrete elements.

From these examples, three main large groups of digital fabrication strategies for concrete apparently emerge, namely, subtractive technologies for formwork fabrication in general, in which 3D milling is the most developed strategy already common in the construction industry as a general solution for customized concrete forms; the emerging 3D printing of formwork; and direct 3D printing of concrete, which in recent years has seen considerable experimental advances. Against this background, it is natural to posit that, as the digital turn has empowered the architect to virtually design and build anything he desires, and that consequently, designing can become unlinked from making, digital tools can be regarded as a means for automation or atectonic, acritical technological solutions for complex architecture.

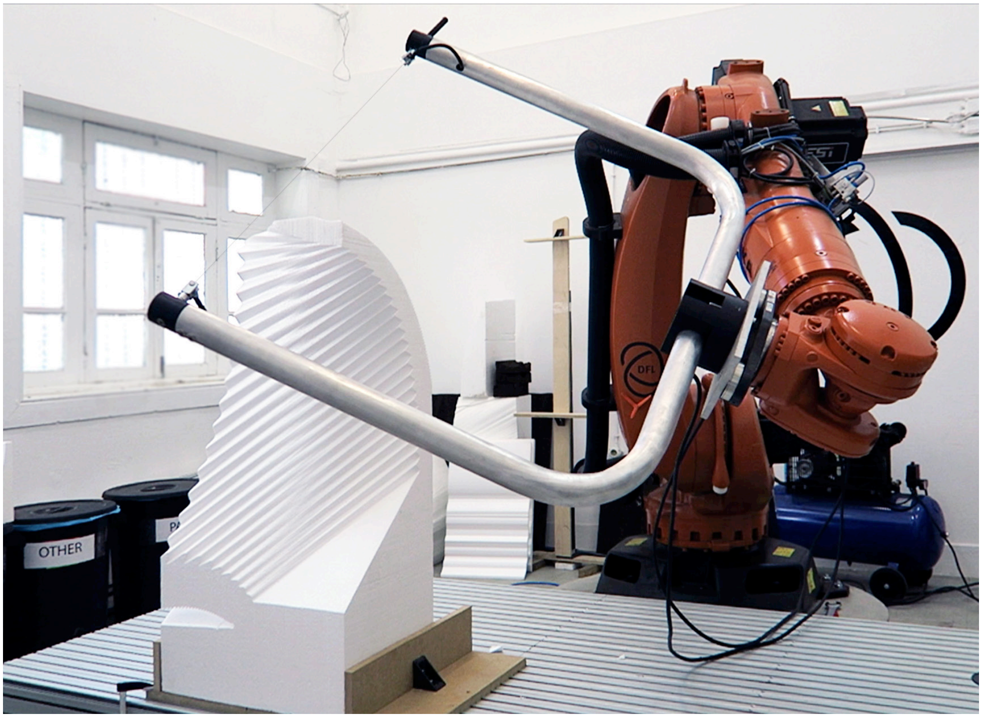
As such, given this background, it is relevant to explore solutions that balance their technical capability for automated construction and their design potential while simultaneously responding to contemporary environmental demands.

Towards this objective, this paper centres on one specific digital fabrication tool for concrete architecture, robotic hot wire cutting, with a focus on the emerging automation, design and sustainability opportunities of its inherent subtractive mechanic of slicing. By combining the findings of a set of four experimental prototypes developed to explore these issues, we propose a possible answer to the question: *How can digital fabrication tools balance the allure of automation, the responsibility of sustainability and the drive for artistic production?*

2 Robotic Hot Wire Cutting

Within the large group of subtractive digital fabrication strategies for concrete formwork, lies robotic hot wire cutting. Within this classification, robotic hot wire cutting (RHWC) is considered an indirect, subtractive, 3D cutting process for concrete construction. In other words, a digital fabrication process that produces formwork for concrete, by slicing volumes of suitable materials.

At its core, RHWC is an expansion of industrial wire cutting processes usually applied as a fast process for cutting large volumes of material. Traditional wire-saw cutting is a process by which a tensioned fibre or metallic wire is used as an abrasive tool to slice or cut materials such as clay (pre-historic wire saws), wood (scroll-saws) and stone (diamond-wire saws).[3] Hotwire cutting is a development of such processes, substituting the abrasive action with heat. Hot wire cutting machines have been developed since the 1930s for a variety of materials such as fabric, wood, ice, glass, thermoplastics in general and expanded polystyrene (EPS) in particular, with more recent developments applying this slicing logic with different numeric control mechanisms.



Thus, robotic hot wire cutting is a digital fabrication technology that employs this same slicing strategy, enhanced and adapted to the construction industry, by employing a hot wire end-effector attached to a multi-axis robotic arm (Figure 2). This drastically increases the freedom of movement and scale of other wire cutting tools. This setup can thus be used as a digital fabrication tool by directly translating geometric information from a 3D model and cutting complex-shaped components in foam-like stock materials such as EPS which can in turn be used as formwork for in-situ or precast concrete elements.

3 Exploring RHWC for Concrete Architecture: Four Experimental Prototypes

To explore the possibilities of this technology and its applicability in architectural thinking, four exploratory prototypes were developed, with a focus on characterizing its use, optimizing procedures and studying different design aspects. All prototypes were created within the scope of producing formwork for non-standard curved concrete elements, such as panels or self-supporting structures. The different prototypes as well as their key issues are summarized in Figure 3.

Fig. 2 The robotic hot wire cuttig setup at DFL/CEAU/FAUP facilities. A 6-axis Kuka industrial robot and a hot wire end effector tool.

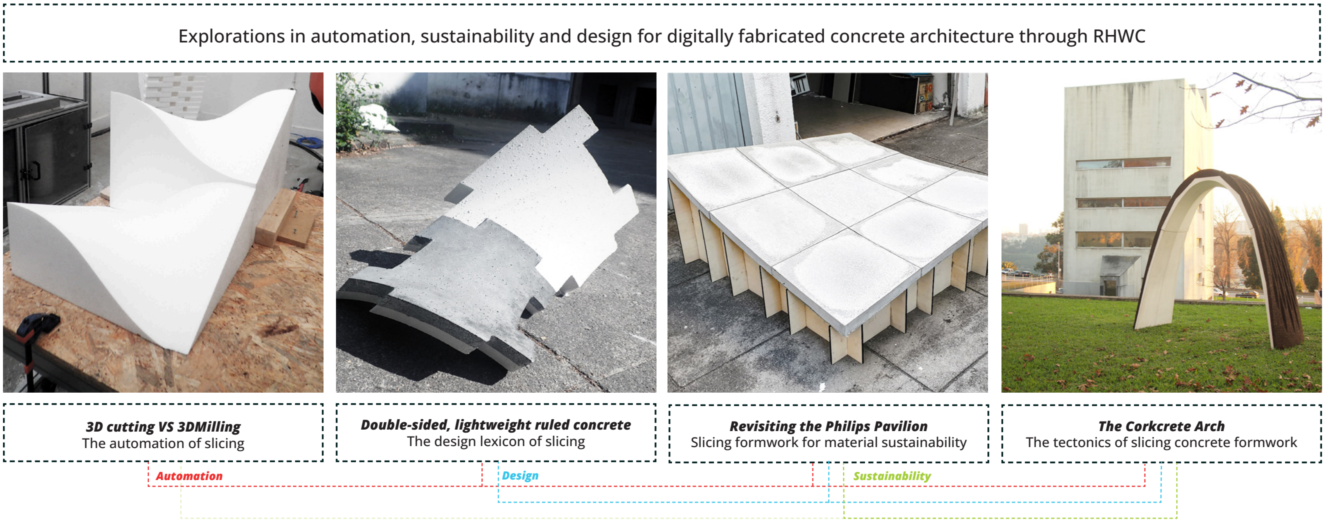


Fig. 3 Prototype A: RHWC vs 3D Milling; Prototype B: MSE panels; Prototype C: Revisiting the Philips Pavilion; Prototype D: The CorckCrete Arch (developed at DFL/CEAU/FAUP, between 2015 and 2019, by the authors).

Most digital fabrication processes are automated to a certain degree, considering that at its base, digital fabrication entails the translation of digital geometric information into machine code in order to transform physical matter without human labour. One key issue of all automated processes is the issue of speed which translates to processing time and eventually costs. Prototypes A (1 and 2) were designed to understand how the process of slicing in RHWC compares to the process of carving in 3D milling, considering machining time, finishing quality and geometric accuracy of a designed curved surface.

With the procedural and geometric basis established, Prototype B was developed as a multi-faceted test to explore the possible formal, textural and material design languages stemming from the slicing process of RHWC, as well as developing a formwork design strategy to achieve these objectives.

With a RHWC formwork design strategy developed, and also the notion of the material optimization of slicing, derived from Prototype A, Prototype C was developed as an exercise in increasing the sustainability of the formwork fabrication process by maximizing material usage and thus minimizing waste generation, capitalizing on the cutting procedures of RHWC. This objective simultaneously led to the exploration a particular set of surface subdivision designs, directly related to the material optimization process.

Finally, Prototype D was developed as a final experiment, combining all previously explored strategies and methods. It tested them in a full-scale, self-supporting structure, showcasing the procedural and material optimization of RHWC as well as the relation between design language, material and digital fabrication strategy. In the following sections, the findings from each experimental prototype are discussed and linked to the main issues raised.

3.1 Automation in Slicing: 3D Cutting vs 3D Milling

Automation is one of the cornerstones of the fourth industrial revolution in general but also in the specific case of the construction industry. In effect, it concerns the ability to produce architectural forms with increasing levels of complexity, precision and speed, directly from digital information, without the need for human labour.

In this regard, the use of computer assisted 3D milling processes for EPS formwork is one of the most used strategies for non-standard concrete architecture today. Nevertheless, as a general digital fabrication solution for complex concrete architecture, it presents two key issues: high production times and high levels of material waste in production. These issues are compounded by the consequent large operating costs that ultimately result in reducing the availability of such design solutions to more general architectural practice.

The main difference between 3D milling and the 3D cutting process of RHWC lies in its slicing logic. While the first works by successively removing material, describing lines at increasing depths in 3D space, point by point, depending on the end tool diameter, the second operates by describing a 3D cutting surface in space, line by line, slicing out a volume of material (Figure 4). Moreover, in 3D milling there is always a trade-off between surface smoothness and fabrication time, where faster milling operations generally result in rougher surfaces.

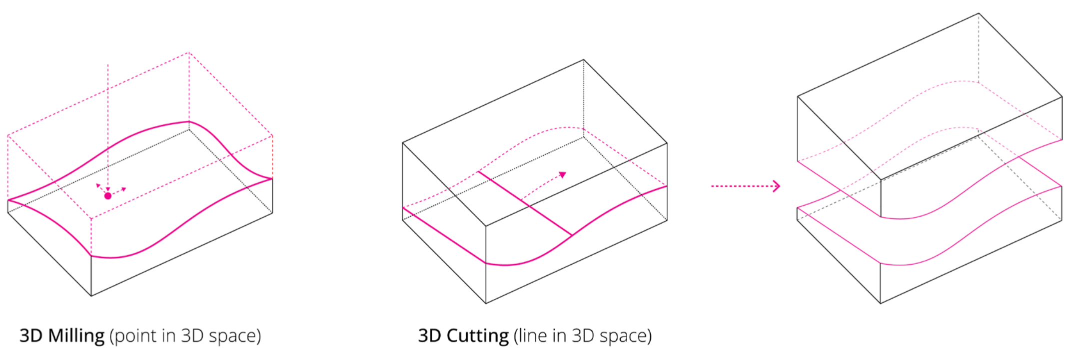
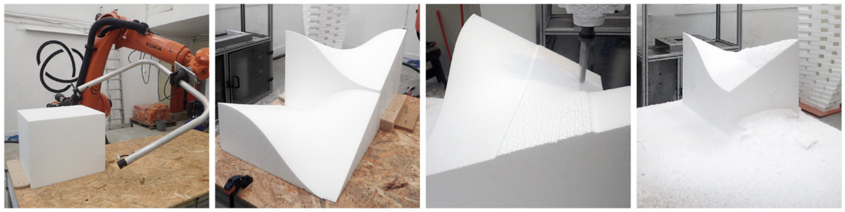


Fig. 4 The material transformation logics of 3D milling and 3D cutting (by authors).



	HOTWIRE	MILLING		
Operations	**Cut 1**	**Mill Rough**	**Mill Finish A**	**Mill Finish B**
Stock dimensions	500×500×600	500×500×600	500×500×600	500×500×600
Surface area	0.33 m^2	0.33 m^2	0.33 m^2	0.33 m^2
Step over	-	9 mm	3 mm	1.5 mm
Time	**37 s**	**6 m**	**49 m**	**1 h 47 m**
Speed	1.85 min/m^2	18 min/m^2	2.5 h/m^2	5.4 h/m^2
Surface quality	high	low	medium	high

Fig. 5 Comparison RHWC and CNC milling (developed at DFL/CEAU/FAUP, in 2018 by the authors).

This distinction in material transformation logic has two major consequences: severely lowering the necessary fabrication times and reducing material waste generation. Figure 5 demonstrates a series of initial cutting experiments developed to compare 3D milling and RHWC for similar geometries, focusing on changes to the fabrication time of curved surfaces, considering different milling strategies.

The accompanying table shows fabrication times for the definition of equal ruled surfaces, with 0.33 m^2 of surface area, in a 500 × 500 × 600 stock block of EPS150, using a RHWC setup and three different 3D milling operations. From these values, it is clear that, for similar surface smoothness (a defining factor for casting moulds), RHWC represents a reduction of approximately two orders of magnitude, or simply put, an improvement from hours per square metre, to minutes per square metre of resulting surface area.

Another feature of slicing in opposition to milling is that in the case of the former, the description of the desired casting surfaces does not entail the destruction of the stock material. The result of one cutting motion is two separate volumes of material. In the case of 3D milling, the result of defining one casting surface is the destruction of half of the stock material. Not only does this increase material usage for the same potential end result (two halves of a mould), it also results in a large volume of material waste, in the form of EPS powder.

To clarify these issues and to set a baseline to which compare all further experiments, a prototype was developed to study the creation of customized precast concrete components, at construction scale, using exclusively 3D milling (Figure 6).[4] It consisted of a set of two precast panels, of variable double curved geometry. Although the precise fabrication of complex concrete surfaces using digital fabrication was achieved, and the resulting double curved surfaces were not replicable using RHWC due to their non-ruled nature, the total processing time using a 5 mm milling bit was approximately 10 hours for the five mould parts necessary, confirming the previous approximated time. In the process, a volume of approximately 0.4 m³ of waste was produced from a starting volume of 0.6 m³, corresponding to about 37% of material utilization.

Although there are evidently benefits for CNC milling, such as a greater geometric freedom and precision, without the limited lexicon of ruled surfaces, the processing times and costs were somewhat prohibitive for such a customized design.

While the ability to produce forms without restrictions is certainly a relevant feature, we believe that it is not a defining necessity.

4 Pedro Carvalho, Sandra Nunes, José Pedro Sousa, "Elementos Compósitos em Betão com Geometria Complexa por Processos de Fabrico Automatizado," *5as Jornadas Portuguesas de Engenharia de Estruturas*, Lisbon, LNEC, 2014.

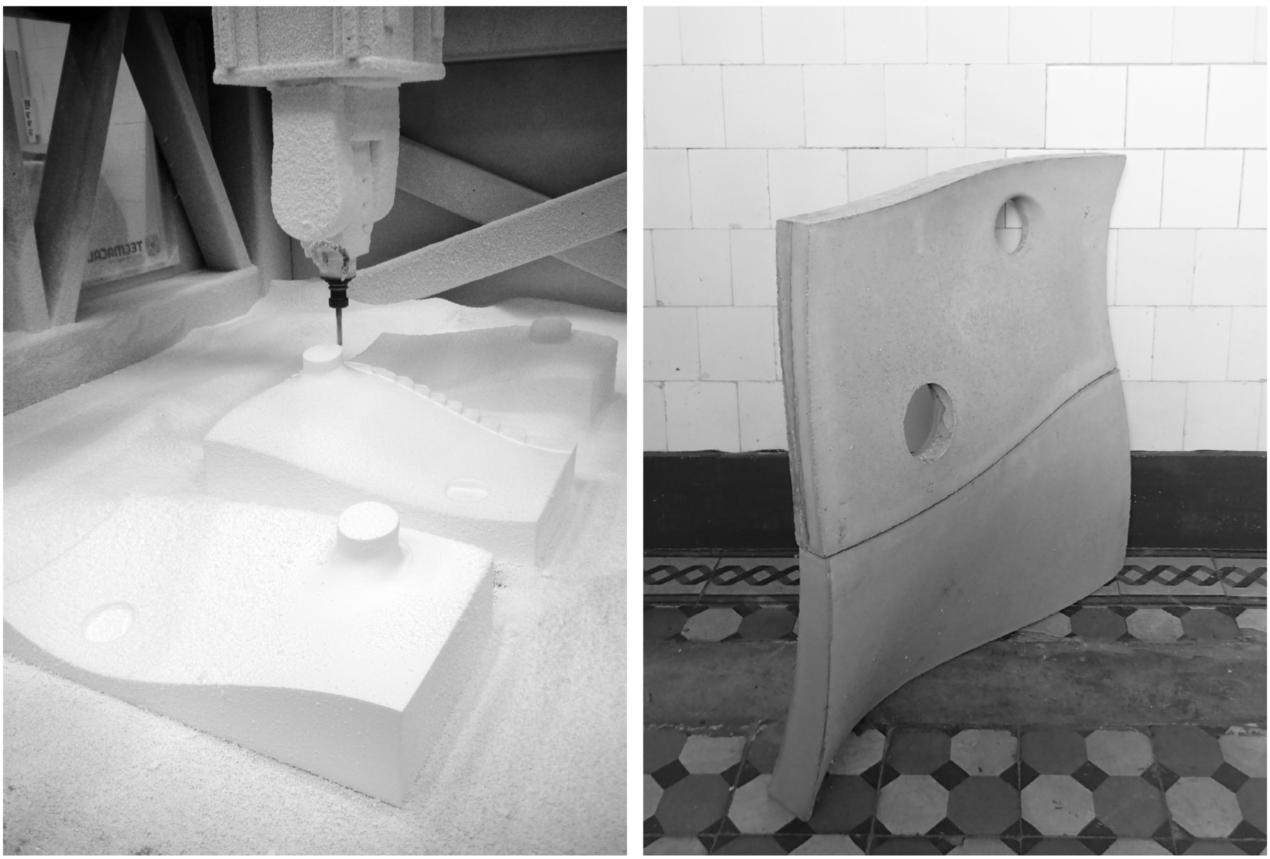


Fig. 6 Prototype A. 3D milled, customized concrete elements of variable double curved geometry (developed at DFL/CEAU/FAUP, in 2014, by the authors).

Moreover, at construction scale, this issue is less relevant as the larger dimensions can enable more satisfactory rationalization strategies of general double curved geometries, still employing the vocabulary of ruled surfaces.

As such, RHWC can be an example of digital tools as technological enablers of complex architectural solutions, but also an example that providing such solutions can be achieved without recurring to expensive, time-consuming processes. In this case, RHWC represents what we can call a relevant social democratization of complex geometries through cost-effective automation.

3.2 The Design Lexicon of Slicing

As mentioned, the main feature of robotic hot wire cutting in the production of concrete formwork is the use of a 3D cutting logic (slicing), which corresponds to the movement of a cutting line in 3D space. This spatial line movement defines a particular subset of geometries, resulting in the inherent limitation of RHWC to a formal lexicon composed exclusively of ruled surfaces.

In general terms, a surface is ruled if through all of its points, at least one straight line can be passed that lies on the surface. Many particular ruled surfaces exist, from simpler ones such as the plane, the cylinder and the cone, to more complex ones such as the hyperboloid, the conoid, the hyperbolic paraboloid and the helicoid as well as other general ruled surfaces, defined by two directrices and one generatrix (the surface defining line). Many of these geometrical shapes have featured extensively in concrete architecture, particularly in the second half of the 20th century, for instance in the thin lightweight concrete shells of Eduardo Torroja and Félix Candela.[5] More recently, ruled surfaces have also seen use as rationalization strategies for general freeform surfaces.[6] In this sense, RHWC is defined by this constraint, but it can simultaneously be a prospect for design exploration.

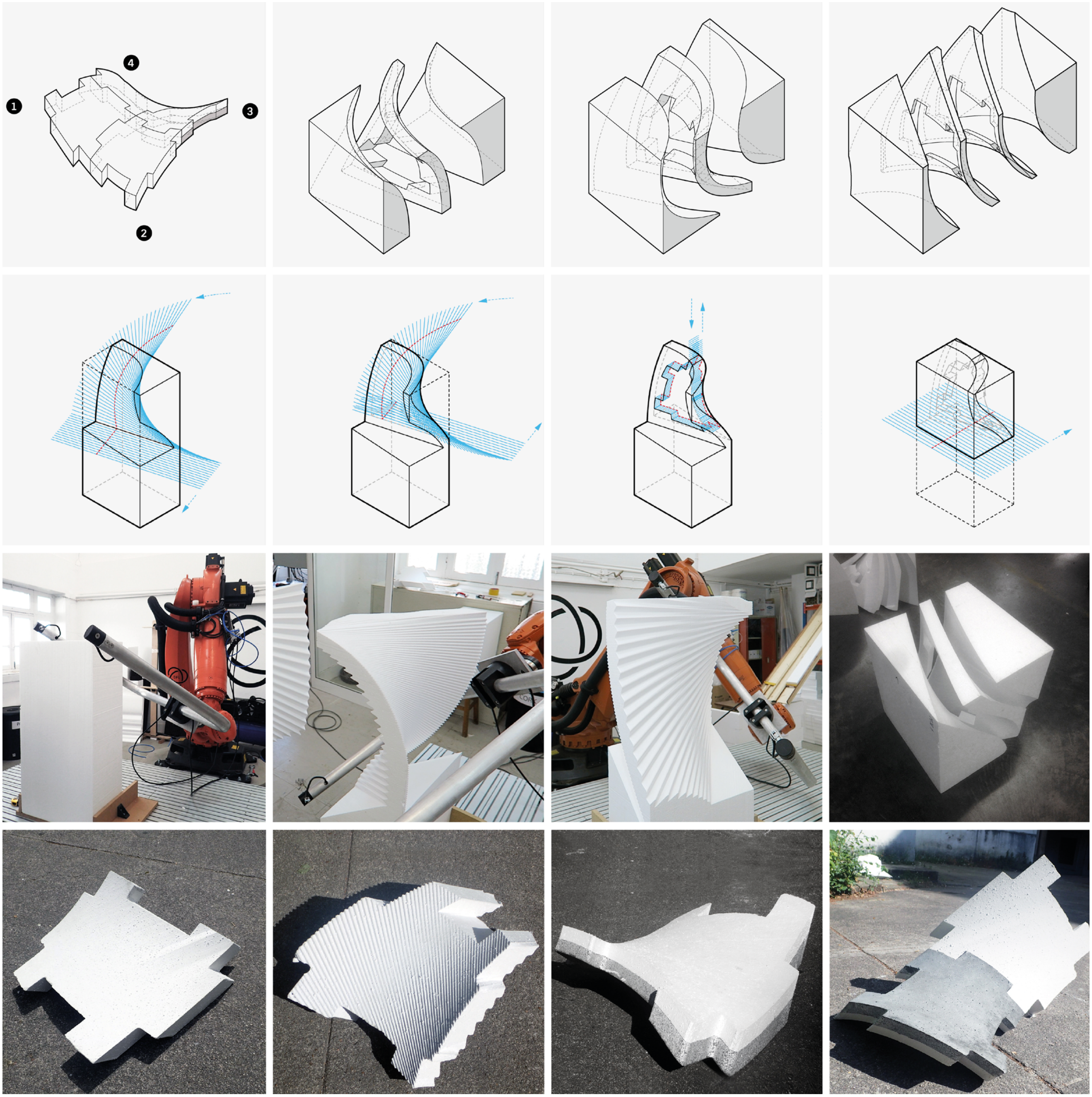
From this key geometric logic, several questions can be put. What forms can actually be created and how can this logic and its constraints apply specifically to formwork design for the casting of such forms? What other opportunities or difficulties arise that delineate a more complete design lexicon, regarding not only form, but also surface qualities and material properties?

The MSE panels were a prototype developed to characterize this process in a practical setting, focusing on addressing three design aspects: form, surface and composition, in the creation of precast, lightweight, double curved concrete panels (Figure 7).[7]

The system was composed of a set of three interlocking panels, inspired by the geometry of mechanically stabilized earth systems (MSE), projected onto a hyperbolic paraboloid surface.

5 Alfonso Basterra, "Félix Candela y el borde libre. El caso de la capilla de Palmira de Cuernavaca," *Bitácora Arquitectura* 5 (2001): 38–47.
6 M. Bartoň, Helmut Pottmann and Johannes Wallner, "Detection and reconstruction of freeform sweeps," *Computer Graphics Forum*, vol. 33, no. 2 (2014): 23–32.
7 Pedro Martins, Paulo Campos, Nunes and Sousa, "Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting – Form, Texture and Composition," in *Real Time – Proceedings of the 33rd eCAADe Conference*, vol. 2 (Vienna: Vienna University of Technology, 2015), 341-351.

Fig. 7 [opposite page]
Prototype B: The MSE Panels;
(top to bottom rows)
a) panel geometry and layered mould design for panels 1, 2 and 3;
b) cutting routine for panel 4 (front cut, back cut, perimeter cut, bottom cut);
c) RHWC fabrication process and final mould for panel 1;
d) finished parts showcasing textured surfaces, variable compositions and two assembled panels
(developed at DFL/CEAU/FAUP, in 2015, by the authors).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One of the main issues solved by this prototype was the particular geometry needed for the closed moulds necessary to actually cast concrete elements. While the issue of creating a general ruled surface in EPS was not difficult, as was demonstrated in Prototype A, the moulds for the interlocking geometry designed presented the added difficulty of creating an interior cavity with a jigsaw-like perimeter.

Thus, to materialize this design, a modular layered mould system was developed, taking advantage of the cutting properties of RHWC. In effect, each wire cut effectively results in two ruled surfaces, which can be separated, creating a space for casting. By chaining one or two sequential slicing operations on a single stock material block and conserving all resulting parts, a multi-part mould can be achieved that can be closed and cast, resulting in the desired elements without any excess material needed. To account for the jigsaw-like perimeter, the basic layered mould was composed of three parts: a front side, a back side and one interior part, containing a ruled perimeter boundary (Figure 7a).

Using this mould design and fabrication strategy, the moulds were cut from stock EPS blocks with 1000 × 500 × 350 mm, in a sequence of four or five cuts, taking approximately seven minutes per finished mould (Figure 7b). Although separated in three panels, the precision of the process allowed for the definition of the desired overall continuous ruled surface between all the components, within construction margins.

What was also clear was that the geometrical lexicon of ruled surfaces was not a mere repetition of traditional shapes. The use of a digital modelling environment, while still working within the ruled constraint, allowed for an expansion of possible forms, which were easily translated to the materialized surfaces. At a construction scale, there was no practical geometrical limitation on the desired surfaces, concerning minimum curvature radii and other geometrical features, impossible to reproduce using traditional construction methods. On the other hand, the issue of form is more complex than the mere description of a pre-designed surface. In opposition to other (more automated) processes such as 3D milling and, to a degree 3D printing, the ruled forms of RHWC are the result of a precise interplay of several factors such as cutting speed and temperature, as well as the particular definition of movement vectors along the ruled surface directrices, where all can be controlled for specific outcomes.

The relation between surface texture and the digital fabrication strategy of RHWC was also explored here and can be defined as twofold. On one hand, again depending on cutting speed, temperature and geometry, the robotic movement of the wire leaves visible marks in the finished concrete surfaces, directly imprinted from the EPS moulds, as a material fingerprint of its creation process. On the other hand, on top of any overall ruled surface, such as was the case in the MSE panels, this linear slicing logic can be further explored to produce different aesthetic textural effects within a ruled vocabulary. These features, which were also summarily explored in this prototype and others can be read in comparison to traditional explorations of formwork traces on exposed concrete surfaces, expressing a direct relation between form and construction process.

Finally, building from this logic of slicing and its speed and material optimization, new material compositions in concrete elements can also be explored. By further exploring this layered mould strategy, a layered materiality of concrete was developed through the idea of sequential casting of concrete with different material qualities. In this case, the second panel of Prototype B was cast in two parts, composed of two different mixes of concrete, alternating between limestone filler and fly ashes, resulting in facings with different colorations (Figure 7d).

This results in the possibility of creating differential double-sided or sandwiched concrete panels, with complex geometries and varied material properties. Although only colour differences were explored, it is possible to envision other characteristics being relevant from an aesthetic or functional standpoint – variations of concrete properties such as colour, texture, density, thermal insulation and others.

While Prototype A defined the basic advantages and possibilities stemming from the automation of slicing of RHWC, what was relevant in these MSE panel prototypes was twofold. Firstly, the validation of the previous findings in actual cast concrete elements, but more relevantly, the characterization of the possible design lexicon, specifically linked to RHWC. A design lexicon which can be explored in a multitude of qualities, interconnecting the geometry of ruled surfaces, the surface effects of slicing and the material effects possible from layered mould strategies.

3.3 Sustainability Through Slicing

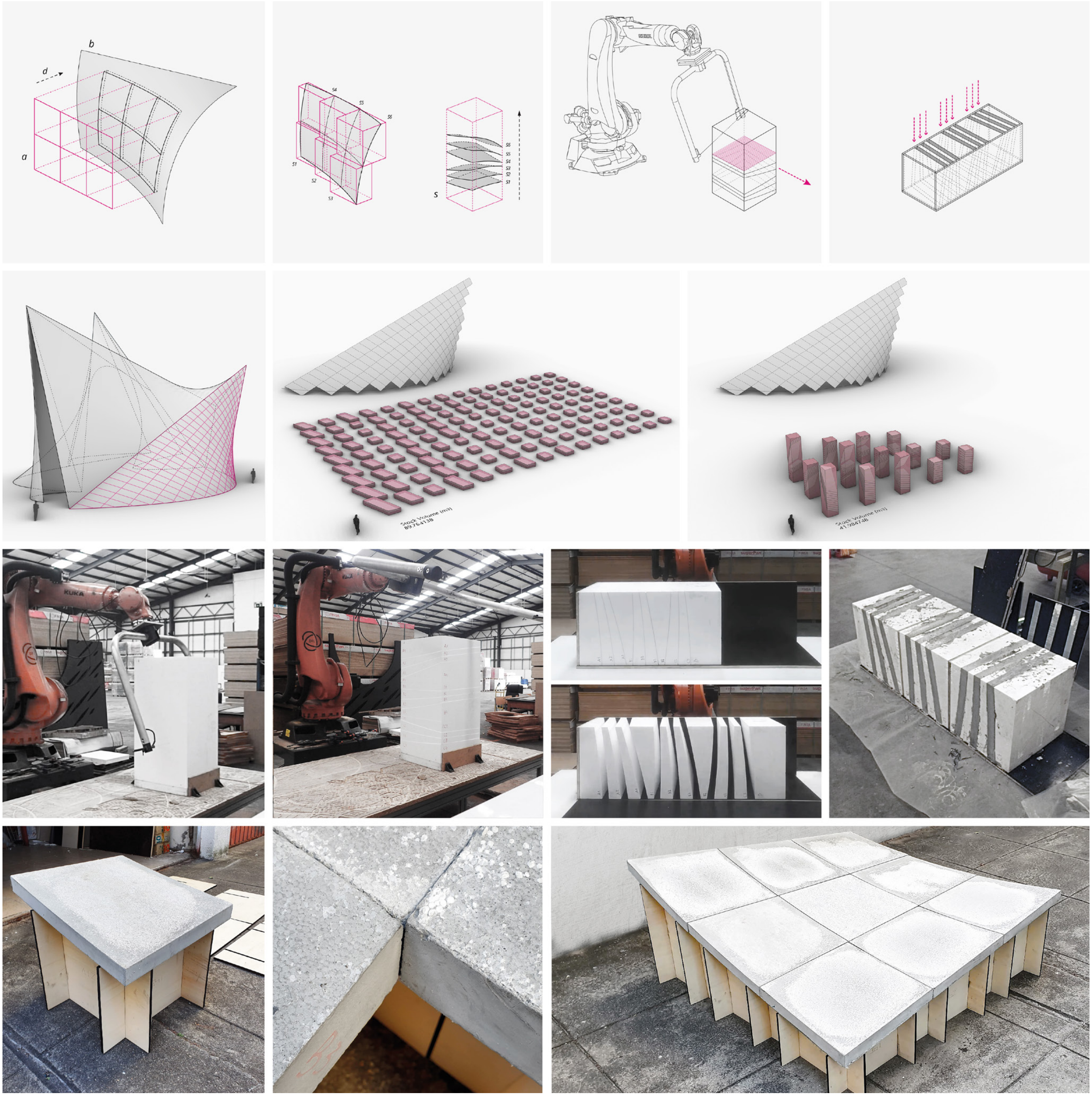
In addition to the actual production of cement, which is usually alluded to as one of the main sustainability issues in concrete construction, the production of formwork also represents a large part of costs, labour, material usage and energy expenditures in concrete building.[8] As such, optimizing this process can lead to relevant improvements in the overall sustainability of the concrete construction process. As was previously established, the slicing logic of robotic hot wire cutting has an inherent advantage of being able to define casting surfaces without destroying a large portion of stock materials in a fast and energy-efficient manner. This represents the possibility for increased sustainability by optimizing material expenditures and consequently, reducing waste generation.

Prototype C – Revisiting the Philips Pavilion explored this issue, by expanding and optimizing the previously defined strategy of the layered mould, combining it with a tailored surface subdivision logic to minimize material consumptions (Figure 8).[9]

The formwork strategy draws inspiration from the precedent of mould batteries, used for the large-scale repetitive production of concrete panels. Its central feature is that multiple elements can be cast side by

8 David W. Johnston, "Design and construction of concrete formwork," in *Concrete Construction Engineering Handbook*, ed. Edward Nawy (Boca Raton: CRC press, 2008), 225; Carmen Llatas, "A model for quantifying construction waste in projects according to the European waste list," *Waste Management* 31, no. 6 (2011): 1261–1276.

9 Martins, Nunes, Campos and Sousa, "Rethinking the Philips Pavilion Through Robotic Hot Wire Cutting. An experimental prototype," in *Architecture in the Age of the 4th Industrial Revolution – Proceedings of the 37th eCAADe Conference*, vol. 3 (Porto: Faculty of Architecture University of Porto, 2019).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side, like vertical shelves, if their boundary geometry is aligned throughout. In standardized solutions, this is used for flat panels, but with the use of RHWC and EPS moulds, several ruled slices can be performed sequentially in a large block of stock material, each defining a surface that can afterwards be separated and cast (Figure 8a).

Using Le Corbusier and Iannis Xenakis's 1958 Philips Pavilion as a starting point, this experimental work focused on exploring different surface subdivision designs for one of its ruled surfaces.[10] By defining an overall tessellation strategy, based on one repeating boundary shape for all panels and projecting this shape onto the surface in a selected direction (minimizing distortion for individual panel boundaries), the resulting 3D panel surfaces can be vertically stacked in an extrusion of the original boundary – the stock material, to be sequentially sliced using RHWC.

Using these geometrical rules, the selected hyperbolic paraboloid surface was subdivided into 135 different panels, choosing a square panel boundary for purposes of simplification. Although with limited inputs (boundary polygon and projection direction), the design explorations could be tailored for different goals, from panel size, to panel curvature, to the minimization of panel variation or simply exploring different tessellation shapes, not limited to the original generatrix directions of the Philips Pavilion.

All of the resulting panel geometries could then be automatically sorted and nested into stock EPS blocks in groups of 10 panels, resulting in 14 formwork stacks (Figure 8c). As an exercise, this subdivision and the corresponding layered mould strategy was compared again with the more traditional approach of 3D milling, where each panel requires one mould milled from its own stock block. Comparing material expenditures for both processes demonstrated that, while approximately 90 m^3 of EPS material was needed for the standard 3D milled moulds, for the same geometry, using the RHWC layered mould strategy only 42 m^3 sufficed.

In this case, the layered mould strategy corresponded to 50% less material volume, when compared with 3D milled, single facing formwork for the same surfaces, or 75% less, if closed moulds, requiring two casting surfaces to be considered (Figure 8b).

To further test the viability of this process, a partial section of the Philips Pavilion surface was then materialized with this methodology. The final experimental prototype was composed of a set of 9 panels at a 1 to 2 scale, with approximately 50 × 50 × 5 cm each defining a continuous double curved surface area of 2.25 m^2. The necessary formwork elements were fabricated in approximately 10 minutes, and afterwards assembled, braced and cast with a self-compacting, fibre-reinforced concrete mix. The resulting set of panels was able to be accurately assembled into the desired geometry (Figure 8c,d).

Generally, these explorations show that digital processes can be tailored for enhanced material efficiency and sustainability, producing

10 Y. Xenakis, C. G. J. Vreedenburgh, A. L. Bouma, F. K. Ligtenberg, and H. C. Duyster, "The Philips Pavilion at the 1958 Brussels World Fair," *Philips Technical Review* 20, no. 1 (1958): 1-27.

Fig. 8 [previous page]
Prototype C – Revisiting the Philips Pavilion; (top to bottom rows);
a) panel stacking logic;
b) subdivision and stock volume comparison for milling strategy and layered mould strategy;
c) robotic hot wire cutting of a mould stack, mould assembly and cast panels;
d) finished panel and assembled prototype (Developed at DFL/CEAU/FAUP, in 2019, by the authors).

11 Sousa, and Martins, "The Robotic Production of the GRC Panels in the CorkCrete Arch Project – A stratified strategy for the fabrication of customized molds," in *Complexity & Simplicity – Proceedings of the 34th eCAADe Conference*, vol. 2 (Oulu:University of Oulu, 2016), 153-160.

relevant change. Moreover, it demonstrates how this goal can also be explored as a driver for architectural language maintaining coherent relations between material, process and form.

3.4 The Tectonics of Slicing Concrete Formwork

All previous prototypes addressed particular aspects of concrete architecture, empowered with robotic hot wire cutting, from the understanding of its key working principles and automation benefits, to the application of its slicing logic in the definition of specific moulding strategies and the exploration of the resulting design lexicon, and its application in more sustainable solutions and the possible design implications.

As such, a more complete vision was necessary that could integrate the previously explored aspects of RHWC at various levels, and test them in a complete, functional, full-scale, tectonic structure. Thus, Prototype D – the Corkcrete Arch (Figure 9) was proposed as a light precast material system, leaning on the automation possibilities afforded by the robotic fabrication process and the specific benefits of the slicing logic of RHCW for mould making. It focused on the possibility of creating easily assembled and customized prefabricated elements suitable for industrial precast settings, compatible with the RHWC technology.[11]

To fulfil this purpose, the Corkcrete Arch was developed as a self-sustaining arch, composed of three connected structural GFRC (glass-fibre reinforced concrete) elements, faced with 18 cork panels. From a design standpoint, the geometry of the Corkcrete Arch was tailored for both its structural performance and its materialization mainly through RHWC. This defined the overall geometry as a set of two intersecting, convex ruled surfaces, originating in a central catenary curve, with a variable thickness profile which reduced the weight in the top section of the arch (Figure 9a).

These complex geometrical features presented challenges that were overcome through a refined layered mould strategy, tailored for this specific geometry and a revision of the arch geometry and subdivisions to fit available fabrication and material boundaries. The design and fabrication strategy for the moulds implied the subdivision of each of the three moulds into longitudinal halves, along the central catenary curve to avoid any convex sections. These were further divided into several mould sections as in previous prototypes: a base surface, a perimeter surface (defining the overall boundary of the non-rectangular panels and the structural flaps of the GRC with variable heights) and a top surface for fitting the planar cork panels. While all other surfaces were cut using RHWC, the perimeter surface was defined using a milling operation to more easily define the variable contour of the components when compared with the process used in Prototype B, without substantially increasing production times (Figure 9b). The resulting core of each perimeter cut was used as filling and thermal

Fig. 9 [opposite page]
Prototype D – the Corkcrete Arch;
(top to bottom);
a) Corkcrete Arch assembly design, main geometrical features and formwork design;
b) RHWC process for central part mould;
c) GFRC spray process and demoulded part;
d) assembled arch
(developed at DFL/CEAU/FAUP, in 2016, by the authors and Pedro de Azambuja Varela).

insulation of the panel. After fabrication, all mould parts were glued, conforming three open moulds to be sprayed with GFRC. This process took place in an industrial precast plant, where the moulds were used without the necessity of developing special equipment or procedures. This process included mould preparation, fastening embedding, mould coatings and the final 15 mm GFRC spray process (Figure 9c, d).

As in the previous case, this revealed that by taking the specificities of formwork design and surface subdivision into account, the process can be used to address specific geometrical challenges, increasing the design possibilities of RHWC, a consideration not unlike traditional concrete construction processes. Additionally, since the necessary subdivisions of the mould became imprinted on the exposed GFRC surfaces, an interesting aesthetic relation between design and fabrication process could be developed. This demonstrated that dimensional limitations to the RHWC layered mould process, which were previously not explored in true construction scale, could be integrated into the apparent GFRC elements and considered in the early design stages. Overall, we considered that the interplay between form, techniques and materials, expressed in the design geometry, material behaviour and the fabrication process of the Corkcrete Arch, as well as the resulting language of precast lightweight self-sustaining components presented a tectonic language which is intimately related with this particular digital tool.

A final relevant point that also became apparent through this prototype was the integration of RHWC into established construction processes. While the multitude of digital tools presented in the first section of this paper demonstrate various avenues of innovation, several come with added difficulties of implementation in established industrial settings. These generally come about due to the necessity of increased technological hardware requirements, materials science or production know-how. In this respect on the other hand, RHWC presents a middle-ground opportunity that can be easily integrated into existing production procedures, materials and processes.

In all, the development of the Corkcrete Arch represented a validation of all previously studied qualities and pointed to their application in full scale constructive systems. In it, form was a result of structural considerations, but also of balancing the constraints and opportunities of the material and the (digital) transformation process employed in its materialization. This stands as an example of how digital tools, like any other tool, can be critically appropriated in architectural production.

4 Balancing Design, Automation and Sustainability in Digital Making

At the current turning point, with the rapid expansion of digital technologies resulting in the notion of a fourth industrial revolution, and the multiple solicitations to architectural production, this paper

12 Thomas Leslie, *Louis I. Kahn: Building Art, Building Science*, Reference, Information and Interdisciplinary Subjects Series (New York: George Braziller, 2005).

considers the question: *How can digital fabrication tools balance the allure of automation, the responsibility of sustainability and the drive for artistic production?* The experimental prototypes presented throughout this paper represented a collection of explorations into several aspects of the use of a particular digital fabrication technology, robotic hot wire cutting, regarding these topics for the particular case of concrete architecture. They represent, as a whole, not a solution, but one potential answer to the question posed.

While several aspects were studied, regarding these three dimensions of design, automation and sustainability, there are still interesting avenues for future developments. First, regarding the issue of sustainability, it is crucial to find other stock materials for formwork that can still work within the logic of slicing but that do not entail the negative environmental aspects of polystyrene foams and can simultaneously be useful for casting concrete. Other mould finishing solutions that result in smoother apparent concrete surfaces also have to be developed if these strategies are to be employed in larger markets. Current solutions using sprayed coatings or other interface materials greatly increase costs and fabrication times. Considering the issue of design, the examples of multi-material concrete composites and lightweight precast elements developed in Prototypes B and D suggest an interesting avenue of exploration, combining materials variability in concrete with variable design intentions in free form (ruled) geometries. Or, in other words, what could the tectonics of a lightweight precast concrete system be, with variable material properties in a layered design logic.

In the construction of the Richards Medical Center, Louis Kahn famously relates an episode where a crane assembling 25-ton precast concrete components dominated the construction site. After an initial negative reaction, Louis Kahn regarded this crane as an agent of meaning for design, comparing it to a hammer and an extension of the human arm.[12] This idea of technology as an agent of tectonic meaning attests to the potential for tools, manual, mechanized or digital, to affect change in architectural production, not only through their more immediate functional value.

As demonstrated, digital tools can certainly be explored for automation, and this automation can bring about positive change, by democratizing non-standard construction methods to wider practice. Its inherent procedural logics can also lead to specific formal and aesthetic vocabularies which can feed architectural design and these same logics can be explored as paths for increased sustainability. Simultaneously, these digitally empowered sustainable strategies can also be explored as particular design solutions. Each of these aspects can assume a central role in design, individually or as parts of a whole.

The use of digital tools, although empowering the design and construction of virtually any form, does not change the fundamental aspect that they can and should be drivers for design in themselves. Thus, the balancing act of using digital fabrication proposed in the research question can be found in the interconnected and simultaneous consideration of each of these aspects at the design stage. In this regard, the potential of such tools lies in their ability to give architects almost seamless control of design and making through digital information. The collected explorations in this paper represent this interpretation, developing an integrated architectural vision of a digital fabrication tool, RHWC, from design to construction.

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