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Tectonics and Material Transformations

Exploring concrete in architecture through digital fabrication processes

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Tectonics and Material Transformations

Exploring Concrete in Architecture Through Digital Fabrication Processes

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Abstract

In the global architectural context of recent decades, the integration and exploration of digital design and fabrication tools has sparked a growing interest in designing progressively more complex and personalized spatial and constructive solutions. While these interests pose significant challenges to the construction industry, they also offer important opportunities for innovation in the field of architecture. At the same time, concrete remains one of the most widely used construction materials in our built landscape and is a traditional material of choice for many architectural styles. Therefore, concrete remains a very relevant material for architecture, but it also holds significant economic and environmental relevance due to its widespread use.

In this context, the general theme of this thesis focuses on digital fabrication technologies and their impact and potentials in the production of concrete architecture.

This thesis argues that by integrating digital fabrication technologies with the design process, it is possible to not only overcome the limitations of traditional concrete architecture but also enable new architectural possibilities in line with both traditional and emerging desires for this material. Therefore, the central question it seeks to answer is: *How can digital fabrication technologies expand the lexicon of traditional concrete architecture in terms of form, surface, and composition, using accessible, sustainable, and tectonically relevant methodologies?*

In order to answer this question, this thesis evaluates the impact of the integration of these technologies in the concrete design and construction process, focusing on three concepts: form, surface and composition. Aiming to expand current possibilities, it proposes and explores a robotic technology (RHWC) as a viable and tectonically significant strategy for a non-standard architecture in concrete, defending its potential both at a constructive and creative level. Through the realization of experimental prototypes, focused on robotic hot wire cutting of EPS moulds, this thesis demonstrates the architectural potential of this technology in terms of creating complex geometries, textured surfaces and variable compositions. Alternating experimentation in laboratory and industrial environments, the technical and economic viability of this technology is also demonstrated, as well as its relevance for the development of new products in this material.

Resumo

No contexto arquitetónico mundial das últimas décadas, a integração e consequente exploração de ferramentas de desenho e fabricação digital tem estimulado um interesse crescente na conceção de soluções espaciais e construtivas progressivamente mais complexas e individualizadas. Estes interesses apresentam hoje desafios consideráveis á indústria da construção e, simultaneamente, oportunidades importantes de renovação do campo da arquitetura. Neste contexto, e tendo em conta não só a sua relevância económica e ambiental, como o papel que desempenha no desenho da paisagem construída, esta tese foca-se no betão e no impacto das tecnologias de fabricação digital na produção de arquitetura neste material.

A tese defende que a aplicação de tecnologias de fabricação digital de uma forma integrada com o projeto pode não só ultrapassar as limitações da arquitetura tradicional em betão como capacitar novas possibilidades arquitetónicas em linha com as vontades tradicionais e emergentes para este material. Desta forma, pretende responder uma questão central: *Como podem as tecnologias de fabricação digital expandir o léxico da arquitetura tradicional em betão, ao nível da forma, superfície e composição, através de metodologias acessíveis, sustentáveis e tectónicamente relevantes?*

Com o intuito de responder a esta questão, esta tese avalia o impacto da integração destas tecnologias no processo de projeto e construção em betão, focando-se em três conceitos: forma, superfície e composição. Ambicionando expandir as possibilidades correntes, propõe e explora uma tecnologia robótica (RHWC) como estratégia viável e tectónicamente significativa a para uma arquitetura não standard em betão, defendendo o seu potencial disruptor tanto ao nível construtivo como criativo. Através da realização de protótipos experimentais, focados no corte robótico por fio quente de mouldes em EPS, esta tese demonstra as potencialidades arquitectónicas desta tecnologia ao nível da criação de geometrias complexas, superfícies texturadas e composições variáveis. Alternando a experimentação em meio laboratorial e industrial demonstra-se também a viabilidade técnica e económica desta tecnologia assim como a sua pertinência para o desenvolvimento de novos produtos neste material.

Chapter 1

Introduction

This chapter introduces the research topics proposed in this dissertation, starting by presenting its general theme at the intersection of concrete architecture and digital fabrication technologies. From this contextualisation, the problem and central questions of the thesis and their corresponding objectives are constructed. The main arguments leading to the investigation are defined here and its structure is also summarised.

1.1 Background

In the disciplinary field of architecture, concrete has a particular character, recurrently distinguished from other traditional materials due to its composite and synthetic nature and its ability to assume virtually any shape. This character has established throughout history, a strong design tradition focused on the desire to explore the architectural limits of this material and on the manifesting of its plasticity and material aesthetics in varied ways. Works such as the Sports Palace by Pier Luigi Nervi, the chapel at Cuernavaca by Félix Candela, the church at Ronchamp by Le Corbusier or the house in la Moraleja by Miguel Fisac are all examples of this exploration, emphasising different aspects of this material.

In the scope of this thesis, we use the term "Concrete Architecture" to refer to works such as these, where the exploration of concrete can be considered a central design theme. Wether by the geometrical formal possibilities it affords, the textural aspects of its apparent surfaces or the material qualities inherent to its changing compositions.

Although there have been different approaches to concrete architecture, the expressive tradition mentioned before, can be traced to contemporary times, following new paradigms, empowered by the use of digital tools. Recent works, such as Frank Gehry's Zolhoff towers, Toyo Ito's crematorium in Kakamigahara and Amanda Levette's Spencer Dock Bridge, demonstrate the continued and renewed interest in exploring the architectural possibilities of concrete in the current context, integrating to this effect, the use of digital design and fabrication tools.

Digital fabrication processes in general and robotic fabrication in particular, have aroused renewed interest in architects, due to their ability to materialize the increased complexity of design made possible through the use of digital modelling tools. This fact has led to the establishment and development of digital fabrication as a research field within the discipline of architecture, surpassing its purely industrial genesis as material transformation processes. In this context, resides the central idea that the study, development and exploration of new construction technologies through the use of digital tools is also a disciplinary area of architecture.

The relation between architecture and technology is not new and has been extensively explored, particularly in the continuous interconnection of architectural practice and constructive technology. It has also been acknowledged in architectural theory increasingly throughout the 20th century. Louis Kahn famously relates the episode of the crane as an agent of meaning for design. While assembling 25-ton precast concrete components at the site of the Richards Medical Center, Kahn compares it to a hammer, as an extension of the human arm (Leslie and Kahn, 2005).

Starting from this idea of technology as an agent of tectonic meaning, in the book "Tectonic Visions in Architecture", Anne Beim (Beim, 2004) poses the question:

> *"...if building-technology and practices of construction are identified as tectonic means and consequently act as carriers of meaning, it is tempting to ask: what happens to architectural expression when building moves from craftsmanship to industrialization?".*

In this contemporary context, we are tempted to ask the question: what possibilities emerge when, after an industrial paradigm of standardization, we move towards a paradigm of personalization and individualization, that prompts us to re-evaluate the relationship between the architect, technology and building materials?

In this architectural context, digital fabrication tools present several relevant potentials. At a technical and technological level, they present new ways of transforming traditional building materials, enabling the design and manufacture of new constructive and spatial solutions. At a methodological level, they present unprecedented potential for the architect to consider and control the construction process from its onset, and inform design strategies with input from fabrication strategies. An idea that can be traced back to the Vitruvian concept of the master builder as the character who controls design through construction and vice-versa. In effect, digital fabrication tools can theoretically close a gap in the traditional architectural process, enabling the transition between design and materialisation through digital information. In his seminal work "The Alphabet and the Algorithm" Mario Carpo (Carpo, 2011) highlights these features of digital fabrication technologies:

> *"Contemporary CAD-CAM technologies have simply obliterated the notational gap that for centuries kept design and construction apart. (…) One can discuss, design, and make at the same time – just as premodern artisans and pre-Albertian master builders once did."*

Among a wide range of materials and construction processes explored through digital processes (Kolarevic, 2004), digital fabrication in concrete has seen considerable expansion in the previous decade. There is now a wide range of tools and processes representing different approaches to the production of concrete architecture through digital fabrication. Processes as diverse as the robotic fabrication of formwork systems, the robotic cutting of precast concrete and the direct

3D printing of concrete elements. These suggest different potentials for an expansion of the language of architecture in concrete, and also present different technical characteristics. and potentially different consequences at a design level.

In a broader social context, the integration of new technological processes in the production of concrete architecture is also particularly relevant. Today, concrete is considered one of the most consumed artificial material in human activity, with about 4,4 billion tons being produced annually. As such, the problem of sustainability related to the concrete industry is presently very pertinent. This is mostly linked to the consumption of resources and the production of waste materials and generation of greenhouse gases that occur in the production of cement.

This issue will hardly be solved in the decades to come. On one hand, the projected population growth and corresponding urbanization needs will ensure increase construction needs for which concrete remains one of the most relevant solutions. On the other hand, cement and concrete sustainable alternatives which can completely offset the carbon footprint of this material are not available in the foreseeable future, considering its ubiquitous nature and simplicity of use in current industrial processes (Habert et al., 2020).

Nevertheless, more surgical solutions can also be employed to offset these issues. In this regard, the production of formwork is also a relevant aspect of the equation. Traditional concrete building processes usually employ formwork systems that can be mostly reusable but this is not the case when considering complex geometries. In such scenarios, reuse is often difficult due to the unique nature of the designs and the low adaptability of formwork systems, resulting in further waste production and environmental expenses.

As such, it becomes relevant to seek production processes that enable the creation of tailor-made concrete architecture, while potentially considering sustainability by optimizing resource consumption and minimizing material waste generation.

Thus, it is possible to ascertain that concrete represents not only a sector of great economic relevance, but is also one of the most relevant materials in the built landscape. It is therefore, the building material which most consequentially impacts human environments and addressing this reality will necessarily have consequences for concrete architecture. In the book "Towards an Ecology of Tectonics", Anne Beim (Beim et al., 2014) defends the need for the sustainability of construction processes to be addressed at the design stage, contributing to an extended discussion of tectonics that includes a new set of demands of this nature.

"Tectonics—a concept with a long tradition in architecture and architectural theory—

> *is comparable to ecology. It relates to the design and assembly of structural elements, and implies a holistic approach to materials, to construction technology and to the design of structures. It is more than merely an instrumental strategy: it extends into the poetic, which elevates it to the status of a cultural practice"*

Thus, in the architectural, technological and environmental context in which we operate today, we believe that the introduction of digital fabrication processes in concrete construction presents one of the greatest prospects for the renovation of our built environment. It Simultaneously represents a particular opportunity to reconsider the sustainability of construction processes and to explore new architectural languages.

1.2 Problem statement and objectives

The research developed in this dissertation arises from a historical context of transition between the traditional, technological, constructive and tectonic culture of concrete architecture and the emergence of new, potentially disruptive, digital materialisation processes. This developing context can be summarised in five relevant points:

1. Traditionally, the production of architecture in concrete involved a complex construction process, with technological constraints at various levels with a relevant impact on the design and final expressiveness of the built work.

2. In the past, the characteristics of this process were exhaustively explored in the design and construction of particularly expressive works in concrete, establishing a concrete tectonic, closely linked to the material and its construction process.

3. The integration of new digital fabrication technologies in this process has the potential to overcome the formal and material limits of traditional concrete architecture, enabling new architectural solutions in this material and potentially expand (or oppose) traditional tectonic concepts of concrete architecture.

4. The advanced, experimental and technological nature of digital fabrication often implies the use of complex, time-consuming and expensive processes, requiring specialized labor and, therefore, accessible only in works of an exceptional nature.

5. In the current socio-economic context, new concerns arise, regarding the environmental, material and economic sustainability of construction processes. Their necessary approach has relevant consequences in architectural design, particularly in the case of concrete.

As explained, in this context, we believe that digital fabrication tools have the potential to overcome some of the traditional limitations of concrete construction and expand the language of architecture in this material. However, we believe that the current contemporary constructive practice does not yet present digital fabrication solutions that balance their technical capabilities and tectonic potential while simultaneously responding to contemporary environmental demands. For this reason, it is essential to study digital fabrication methodologies that integrate these three key aspects (technology, tectonics and sustainability), within the disciplinary field of architecture, thus defining the problem and leading to the central research question of this dissertation:

How can digital fabrication technologies expand the lexicon of traditional architecture in concrete, maintaining or expanding the traditional tectonic concepts of architecture in this material, through accessible and environmentally sustainable processes.

The main general objective of this dissertation is to answer the proposed research question, through a theoretical and practical approach of research by design. By exploring and developing one digital fabrication processes and test innovative fabrication technologies that enable an expansion of concrete architecture in the sustainability and economical viability of non-standard solutions.

At the onset of this dissertation, a full picture of existing digital fabrication strategies for concrete architecture was not yet clear. Many such processes were emerging solutions, with disparate approaches to concrete construction, presenting different limitations and constraints. Nevertheless, it was understood, that a vast number of processes with different technological and material approaches were possible avenues for exploration. As such, considering the presented context and the research question the main objectives of this thesis are:

- Identification and critical analysis of existing digital fabrication processes in concrete, developing an original classification.
- Exploration of robotic hot wire cutting (RHWC) as a process capable of expanding the current possibilities of concrete architecture in a sustainable and tectonically relevant

way.

- Characterization and practical exploration of RHWC in prototypes, built at different scales.
- Exploration of the expressive potential of the use of robotic hot wire cutting processes in prefabricated concrete elements.
- Comparison of this process with more common digital fabrication techniques in concrete architecture.
- Development of specific digital design and fabrication techniques with a view to their inclusion in the construction industry in the Portuguese context.

1.3 Structure and methodology

Towards the stated ends, this thesis is organised in four main chapters. The first chapter, entitled "Introduction", presents the general themes and problems addressed throughout the thesis. The second chapter, "Concrete and Architecture" develops a conceptual and historical context on traditional concrete architecture as a basis for a present reading. The third chapter, "Digital Transformations", presents, classifies and discusses a wide range of digital fabrication technologies in concrete, as a basis for the experimental path of the thesis. In the fourth chapter, "Material Explorations", a set of practical experiences are developed and reported, investigating the architectural potential of Robotic Hot Wire Cutting in the production of concrete elements. Below we present an overview of the structure, contents and main issues developed throughout this dissertation.

Chapter 1: Introduction

What is the context and central research question of this thesis? What is the proposed methodology to address it?

This chapter presents the general theme, identifying in this context the central question of the thesis, the issues addressed and the intended research objectives, building the argumentative structure of the thesis. The research methodology and an overall structure of the thesis are also presented.

Chapter 2: Concrete and Architecture

How was concrete construction technology explored in the creation of architecture through traditional processes? What are the technological limits of such uses?

This chapter contextualises the main topics of the dissertation, elaborating on two main points. The first relates to the material, procedural and tectonic contexts of concrete which are at the basis of the conceptual structure of the thesis. The second, illustrates explorations of this material in traditional architecture. The first point introduces the genesis of the material, identifies its main properties and relevant production methodologies. The traditional tectonic culture is also presented and how it can be applied in the specific case of concrete to establish the three recurring concepts of this thesis - form, surface and composition. The second point demonstrates how the tectonic concepts of form, surface and composition were interpreted in reference works of traditional concrete architecture. Specifically, what types of forms were built, with what technologies and constructive logics; what approaches were made to the expression of the exposed surface in concrete; how material composition was explored at the service of constructive and expressive motivations. The third point concludes this contextualization, summarizing the set of problems within the three topics discussed, delimiting the traditional condition of concrete architecture that we propose to expand through the introduction of digital fabrication technologies.

Chapter 3: Digital Transformations

How can digital fabrication technologies for concrete architecture be categorized and characterised? What are their impact in terms of form, surface and composition?

Given the traditional interests present in the three concepts elaborated in the previous chapter and the existing limitations in the traditional methodologies defined, this chapter analyses the transformations operated in concrete architecture, with the introduction of digital fabrication technologies. This is done through a survey, description, characterisation and classification of the most relevant digital fabrication technologies, in order to clarify the potential and limitations of each, analysing the technology and examples of its application in concrete architecture. A critical analysis and mapping of all processes discussed concludes the classification process. Based on the previous examination of digital processes, elements of an expanded tectonic language for digitally fabricated concrete are also extracted and discussed, using the same conceptual framework defined in the previous chapter. The focus is on the possibilities of creating

a non-standardised formal variety, new technological impressions on exposed surfaces and the role of material compositions in concrete digital fabrication. Based on the previous contents, the analysis of this chapter concludes with the discussion of the limitations that still exist in terms of the feasibility and sustainability of digital processes, establishing the basis for the following experimental investigation.

Chapter 4: Material Explorations with RHWC

How can RHWC expand the lexicon of traditional concrete architecture, in terms of form, surface and composition, in line with traditional tectonic concerns, in an accessible and materially sustainable way?

From the survey and characterisation of technologies and the analysis of the critical problems still existing in the previous chapter, namely in terms of costs, production times and generation of material waste, this chapter focuses on the experimental development of a technology, Robotic Hot Wire Cutting (RHWC). This is done as a demonstration of the possible contribution of digital fabrication to the problem raised through the development of set of practical experiences which are presented here, defining their objectives, methodologies and results.

Chapter 5: Conclusions

What is the architectural potential of RHWC?

In this final chapter, the entire structure of the thesis is revisited and the conclusions obtained are summarised, integrating them within the formulation of the problems and objectives set out in the first chapter. The results of the different experiments carried out and their contributions to developing a definition of the architectural potential of this technology are also reviewed, according to the questions posed at the end of chapter 3. Future lines of possible development of the themes of the thesis are also presented.

Chapter 2

Concrete and Architecture

In this chapter we develop the main concepts surrounding the topic of concrete architecture, relevant to this dissertation. First, a historical reading of the material and procedural natures of concrete, starting from its primordial origins as an agglomerate and evolving to the development of reinforced concrete in the 19th century. Through this evolution, we focus on its aggregated nature, the importance of the concept of plasticity, as well as the relevance of the mould as a central point in considering the building process a source of architectural expression.

We also approach the topic of tectonic theory in architecture in general and in concrete architecture in particular, to establish a set of concepts (form, surface and composition) that can guide further analysis and experimentation into digital concrete fabrication processes. Finally, through a survey of examples of concrete architecture, built with traditional tools, we establish how these concepts were explored in non-digital settings. The topics developed here present a conceptual basis to which we will return in the course of the dissertation.

2.1 Two perspectives on concrete

2.1.1 A material perspective

The etymology of words often reveals important clues about their meaning. In the designation of the material focused in this dissertation, “concrete”, the Portuguese language presents an interesting divergence in terms used in Portugal and in Brazil. Going back in time, the term "betão", currently used in the Portuguese language was appropriated from the French "béton", whose origin, the historian Peter Collins refers to the old French term "betum", meaning "mass of gravel" (Collins et al., 2004), with etymological roots in the Latin term, “bitumen” (Wiktionary, 2022a), describing waterproofing materials or binders. In turn, the Brazilian “concreto” appropriated the English term “concrete”, originating from the Latin “concretus” (Wiktionary, 2022b) from the verb “concrescere”, meaning to coalesce or as an adjective, something solid, hardened. From these two roots, one could say that it is possible to perceive, the duality inherent to this material and the primordial concept of a shapeless mass that coalesces into something solid.

The history of this material is usually told in two chapters, with an interval of 16 centuries between them. It starts from its material origin with the development of pozzolan cement and its use in Roman construction, recurrently referred to as Roman concrete, moving towards its modern reinvention and development in the 18th century becoming the material we know today.

This initial material origin dates back to the use of hydraulic binders in roman construction[1] in the form of a mortar made up of lime and volcanic ash (pozzolan) and large-scale aggregates, called “caementum” by Vitruvio in De Architectura (Pollio, 1914). It was used in the construction of monolithic walls and domes with a permanent stone formwork or through the construction of wooden formwork systems Figure 2.1.

Although there are records of these works today, the centuries following the fall of the Roman Empire saw a return to the use of stone as the main building material which, according to Peter Collins, in the book *Concrete: The Vision of a new Architecture (Collins et al., 2004)*, was more related to its noble character than because of the inadequacy of the technology for building in concrete. The modern incarnation of this material begins to take shape with the develop-

[1] Roman concrete can be considered an innovation on the general use of lime mortars, already in application since classical antiquity, through the addition of volcanic ash, resulting in a more resistant material.

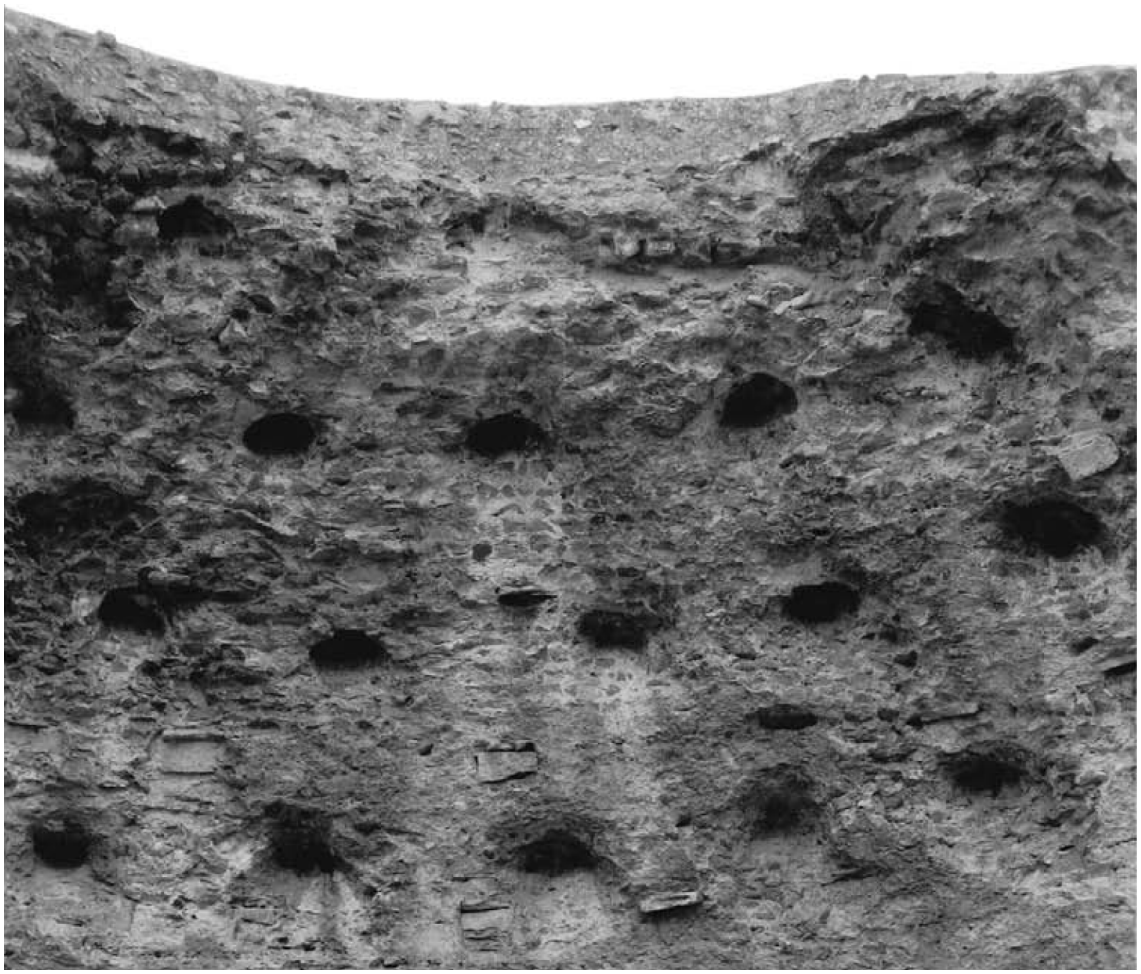


Figure 2.1: Detail of caementa of the dome at the Heliocaminus Baths at Hadrian's Villa (a.d. 125–133)(Lancaster, 2005)

ment of new forms of cement during the 19th century, by Joseph Smeaton, Louis Vicat and Joseph Aspdin with the invention of Portland cement. The turning point in the modern history of concrete as a structural material was however, the invention of metallic reinforcement and the creation of reinforced concrete, based on the experiences of Lambot and Monier. With its subsequent application to structural elements and in complete constructive systems (e.g. Hennebique System) the modern exploration of architecture in this material as we know it was under way Figure 2.2.

Since its original genesis, concrete is a complex and multifaceted material. The term "hybrid" is recurrently used in its description, focusing on the difficulty of establishing a unified definition for this material. In general, it is composed today, as in ancient times, by a combination of a hydraulic binder, aggregates and water in specific proportions, forming a paste (Figure 2.3). From this initial liquid state it hardens and solidifies into a final form. Depending on its use



Figure 2.2: Early developments of reinforced concrete: a) Reinforced planters by Monier; b) reinforced concrete boat by Joseph-Louis Lambot; Hennebique construction system by François Hennebique.

in structural elements or in merely self-supporting elements, it can be reinforced or not. This is certainly a reductive definition, but one that we believe contains within itself the main elements that give it substance and are responsible for its traditionally recognized characteristics. An expansion of this definition to a more complete and contemporary one adds to these basic ingredients, additives and adjuvants,[2] used to influence the initial and final properties of the material (Nawy, 2008a), (Aitcin, 2000). Today, concrete has become a specialized product, with different behaviours, according to specifically produced compositions. As such, a multiplicity of concrete materials can be defined, by manipulating its material composition, affecting any of its properties such as mechanical resistance, ductility, weight, insulation, color, etc.



Figure 2.3: A material genesis of concrete: aggregates, water and binder (Peck, 2014)

Nevertheless, despite presenting substantial differences in composition and application, between its origin in the roman opus caementitium and its modern versions (Lancaster, 2005), it is important to focus, in this context, on the notion of an artificial material, constituted by

[2] Despite being different materials, the application of additives in concrete was already in use in roman construction, for instance, with the addition of eggshells and animal blood.

the aggregation of different natural raw materials and developed by an experimental and technological process. This artificial, technological and hybrid character is summarised by Siegfried Giedion in the seminal work *Bauen in Frankreich, Eisen, Eisenbeton (Building in France, building in Iron, Building in Ferro-concrete.)* (Giedion, 1928):

"It is not extracted from nature as a compact material. Its meaning is: artificial composition. Its origin: the laboratory. From slender iron rods, cement, sand, and gravel, from an "aggregate body", vast building complexes can suddenly crystalize into a single stone monolith that like no previously known natural material ..."

Moreover, the hybrid nature suggested by its composition is reinforced by the duality of states already mentioned: an initial liquid state and a final solid state. This condition results in its central property – the absence of a specific form and the possibility of assuming any shape in its process of "concrescere". This property is at the base of the concept recurrently used in the characterization of concrete architecture: plasticity.

Plasticity, a term derived from material science, pertains to the ability of a material to be deformed permanently by external forces and retain its shape. This is can be considered one of the defining characteristics of concrete. Its ability to change and then retain its shape. In the disciplinary context of architecture, to this material condition of concrete, the term plasticity also adds another level of meaning which can be linked to the field of plastic arts. As an artistic production based on the transformation of physical materials. Thus, plasticity in the case of concrete architecture can be considered not only a physical characteristic of the material, but also the possibility for an intrinsic artistic language.

In the case of concrete, its liquid/solid duality is at the base of this concept of plasticity and is fundamental for the language of this material in architecture. This dichotomy metaphorically accompanies the architectural production of concrete, which both exacerbates a formal fluidity, characteristic of its liquid state, and simultaneously seeks to express the monolithic mass resulting from the solidification process.

This duality is also evident in the recurrent association of this material with two others: stone and mud. At the turn of the 20th century, Perret associated the aesthetics of concrete with stone, affirming the possibility that, *"when well finished"* it could assume *"an appearance comparable to granite, (...) the most beautiful, the hardest, the most durable materials"* (Collins et al., 2004). Opposing this aesthetic, F.L. Wright (Wright, 1928) considers concrete an amalgamation, with no intrinsic material value, finding in its plasticity, the source of its aesthetic value and the main characteristic that distinguishes it from stone. In effect, its ability to change shape.

> *"I should say that in this plasticity of concrete lies its aesthetic value. As an artificial stone, concrete has no great, certainly no independent, aesthetic value. As a plastic material (…) there lives in it a great aesthetic property, as yet inadequately expressed."*

In a more direct way, Paul Rudolph categorically links the aesthetics of concrete to the logic of mud, famously asserting *"Concrete is mud. I work with concrete, not against it. I like mud"*.

As such, we can consider that concrete is in fact an artificial material. A material that coalesces, transitioning between liquid and solid, assuming fluid or monolithic shapes, it can be like mud or stone and it is from this plastic process of becoming that arises much of its architectural value. Moreover, as an artificial material, the technology of its creation is in constant flux and its composite nature opens the opportunity for change as new mixing technologies are developed, adding new material properties to concrete.

It will be relevant to see how these metaphors that encapsulate the materiality of concrete can develop with the emergence of new and potentially disruptive digital technologies. How is the idea of "plasticity" affected? Do digital technologies still interpret concrete as "stone"?. And how does the idea of mud apply to digitally fabricated concrete architecture?

2.1.2 A procedural perspective

In his seminal work, "Concrete", Peter Collins (Collins et al., 2004) goes beyond this material genesis of concrete, highlighting the relevance of a "procedural" genesis that historically relates to pisé construction (rammed earth), focusing not on the material used, but on the process of shaping it. Rammed earth is a constructive technology of simple origin, belonging to a broad family of earth building techniques and based on the compaction of this material inside a wooden formwork. As a relatively respected technique in eighteenth-century construction, for Collins, the development of this construction technology, using more efficient materials through the addition of mortar and aggregates was a natural development (Figure 2.4).

Collins' analysis clearly places more emphasis on the cultural and technological zeitgeist that surrounded the re-emergence and development of concrete than on its accurate historicity, given that the use of wooden formwork for concrete-like materials was already part of Roman technology (Figure 2.5). However, the focus on the mould as a central element in the nature of concrete is particularly relevant here. Collins presses this point, stating that the fundamen-

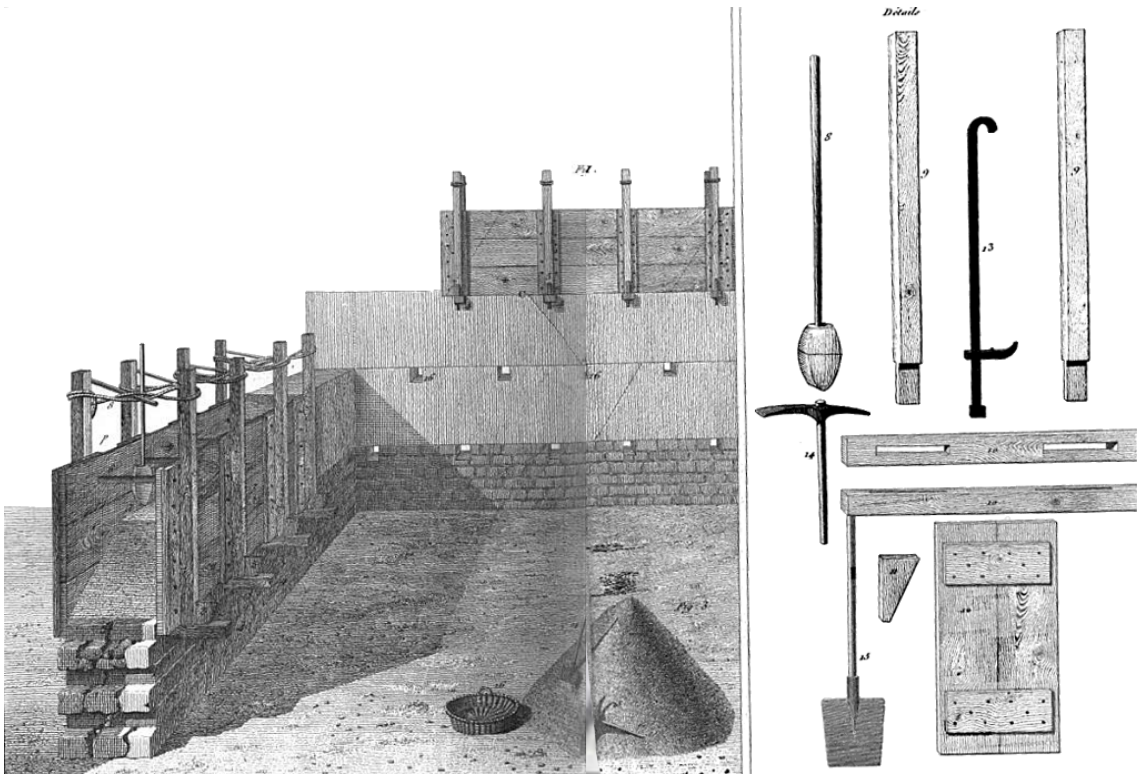


Figure 2.4: Pisé construction system and utensils for its construction (Rondelet, 1812)



Figure 2.5: Formwork traces in the roman forum of Beja, Portugal (I C.E.)

tal characteristic of this material would not be its plasticity, but the process of its delimitation, focusing on the moulding process and on the formwork figure as the origin of the material's nature. In this sense, he quotes F.L Wright, stating *"its form is a matter of this process of casting rather than a matter of anything at all derived from its own nature."*, underlining *"it is in the making of the formwork that the craftsmanship must mainly reside."*. Thus defending the need to consider the formwork as a creative element, distancing it from the acritical duplication of plaster moulds. Collins concludes that the idea behind strategies that avoided the mould (e.g. projected onto reinforcement) were *"the complete negation of all the technological advances that were creating the modern world and a return to a sculptural conception of architecture of the primitive type."*

In the same sense, Andrea Deplazes stated that in order to achieve the possibility of a "liberated" concrete, proposed by the idiosyncrasy of its lack of form, it would be necessary to overcome the "tectonic rigidity" of its formwork. Since Deplazes does not consider any existing technology viable for this purpose, he considers that *"The only way out would be to release the concrete from its formwork – that tectonic, technological and iconographic corset!"*, concluding that the only examples of this approach reduce concrete to its primitive origin in the platonic cave (Deplazes, 2005) .

This idea of the mould as the central theme of concrete architecture has echoed in architectural discourse since the first decades of the 20th century, right up to the present day. Not only as a technological delimiter of form, but also as a possible expressive element through its imprints on exposed concrete surfaces. In the current digital context, it will be relevant to see if formwork is still the defining concept of concrete architecture and if there are new craftsmanships in its design and fabrication through the use of digital tools. Moreover, if its absence dictates in fact the design of platonic, sculptural caves.

Nevertheless, although the topic of formwork can be central in the production of concrete architecture, it should also be possible to find, upstream and downstream from this point in the concrete building process, other design opportunities that can be relevant. In a simplified reading, the concrete construction process requires a series of works, from the definition and production of a specific mix to the construction of the formwork, application of reinforcement, casting, curing and possibly subsequent surface treatments (Figure 2.6).

Each of these stages contains, from the outset, the possibility of being considered as design opportunities, resulting in a multiplicity of aesthetic expressions directly related to the concrete construction process. For instance, in the manifestation of a specific composition, the control

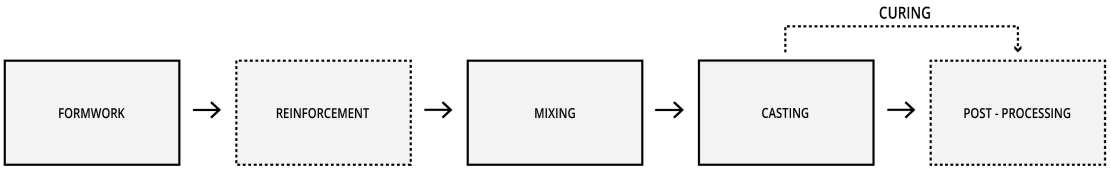


Figure 2.6: Simplified general diagram of the concrete construction process.

of its casting (creating concreting joints) or in the treatment of its exposed surface. In 1927, in an essay with the subtitle "fabrication and imagination" , F.L. Wright refers to the opportunities inherent in the construction process in this material (Wright, 1927):

> *"Ordinarily in itself it has no texture unless the mould leaves it on the surface. It is, however, possible to use fine colored-gravel or crushed-marble or granite in the mixture so the superficial-cement (…) may be easily washed away, leaving the hard gleaming aggregate exposed in almost any color or texture.*
>
> *All composite materials like concrete have possibilities of bringing out the nature of the mixture in some kind of surface treatment, and the materials may be variously composed in the substances mixed to secure these effects of texture and color desired in the finished product."*

Combining the composite and mixed materiality of concrete, the ambiguity of its inherent plasticity and the transformative relevance of the moulding stage, Adrian Forty proposes revising the actual concept of concrete not as a material but as a process (Forty, 2006).

> *"The uncertainty that is such a feature of the aesthetics of concrete undoubtedly has something to do with its common, but mistaken, designation as a material. Concrete, let us be clear, is not a material, it is a process: concrete is made from sand and gravel and cement – but sand and gravel and cement do not make concrete; it is the ingredient of human labor that produces concrete."*

Thus, when the entire process of transforming matter is relevant to architectural design, it is clear that any technological change to this process will also be relevant. The concept of concrete as a hybrid of material and process, becomes therefore, fundamental in the scope of this

dissertation. This broad concept of concrete, results in the possibility of rethinking composition, methodology, intervening in its shaping, treatment of cast surfaces and other opportunities through the integration of digital fabrication technologies.

2.2 Tectonics and cultural tradition

2.2.1 An overview on tectonics

In the previous section, the hybrid nature of concrete, the significance of its formal plasticity and the relevance of the materialization process for creating architecture in concrete were addressed. Thus, the relationship between material properties and the technological processes of their transformation into expressive architectural forms are not only of particular importance in architectural practice, but are also at the center of architectural theory discourse. This is particularly relevant through the concept of tectonics.

Throughout the history of architecture, the concept of tectonics has been successively used as a source of balance in architectural production. When a conflict is identified between the creation of expressive architecture and the processes of its construction, the notion of tectonics is brought into discourse as a conceptual framework, seeking to describe a balanced relationship between these two aspects of the discipline. We believe that the formal freedom enabled by the plasticity of concrete and the complexity of its construction process makes this concept particularly relevant. More so, when the main concern of this dissertation is the use of (digital) technology to impact on the processes of construction.

"What is the tectonic of concrete architecture?" we could ask. *"What is the tectonic of concrete architecture enabled through digital tools?"* we could also ask.

The term "tectonics" derives from the Greek *tekton*, referring to an artisan or builder, originally related to the craft of carpentry, but not necessarily constrained by any material or process (Frampton and Cava, 2001),(Christiansen, 2014). *Tekton* would be one who possessed the knowledge to build and *téchne*, the preceding term, meaning the ability to create. Creating not in a strictly operational sense, but as the application of a deep knowledge regarding materials and processes or techniques and the expression of this into the created form.

In *"The Question Concerning Technology"*, Heidegger (Heidegger, 1977) refers to this process of creation as "bringing-forth" and téchne as the name for the activities and skills of the craftsman

and also, the arts of the mind and the fine arts. A duality of craft and art, inseparable in classical Greek antiquity, which in the linguistic and cultural evolution of the following centuries was separated into technical and artistic, instrumental and poetic aspects. These, Kenneth Frampton argues should be brought together, in order to obtain a work of architecture (tectonically) relevant.

The impact of technological change in this relation is therefore of great relevance in this scope. In effect, for Heidegger, technology, from the Greek *technikon*, meaning that which originates in *téchne*, is not only instrumentality or means, but can have a deeper role in the creative process of "bringing-forth".

> *"Whoever builds a house or a ship or forges a sacrificial chalice reveals what is to be brought forth (…). This revealing gathers together in advance the aspect and the matter of ship or house, with a view to the finished thing envisioned as completed, and from this gathering determines the manner of its construction. Thus, what is decisive in techne does not lie at all in making and manipulating nor in the using of means, but rather in the aforementioned revealing. It is as revealing, and not as manufacturing, that techne is a bringing-forth."*

In the last two centuries, authors such as Karl Botticher, Gottfried Semper, Edouard Sekler and, more recently, Kenneth Frampton, have developed different approaches to the notion of tectonics and its relevance in the field of architecture. Although they present particular and sometimes divergent definitions of this concept, it is possible to identify in their discourse, recurrent approaches to the relevance of building materials and the specific technologies for their transformation into tectonically relevant architectural forms.

One of the first authors to approach this concept, Botticher, studying the role of building systems in architectural styles in "Die Tektonik der Hellen", proposes a conceptual division of the work of architecture in two dimensions: an interior essential form (Werkform), connoted with the structural/functional system of the work and an external artistic form (Kunstform), related to representational or ornamental elements, conductors of meaning. Criticizing what Botticher understood to be historicist approaches, focused on the Kunstform, he defended the need for a relationship of causality and self-reference in these two dimensions, creating a complete, tectonic system. From this reading, our relevant corollary concerns Botticher's reference to what should be the origin of the Kunstform, deriving not only from the structural form, but also from the respective material logics (Bötticher, 1992):

> *"The true essentials have never been seriously considered; the discussion has never actually turned to the source of the art-forms and of the diversity of styles, namely, the structural principle and material conditions on which each is based".*

As such, for Botticher, the construction of new spatial systems and styles was, to a certain extent, directly dependent on the development of new structural systems, which, in turn, could only result from new construction materials.

In 1851, in "The Four Elements of Architecture", Semper divides the archetypal dwelling in four constituent elements: the fireplace (hearth), the foundation (earthwork), the structure/cover (framework/roof) and the wall (enclosing membrane) (Semper, 1989). More relevant, within the scope of this dissertation, is the fact that for each element, Semper assigns a specific material as well as an intrinsic tectonic craft. As such, the fireplace would be associated through fire with ceramics and moulding; the foundation to earth or stone and masonry; the structure/roof with wood and carpentry; the wall to fabrics and weaving. In the same way as each element has a material and its respective transformation process, Semper also assigns them different formal logics, relating the structure/roof with the articulation of discontinuous linear elements and the foundation with a volumetric mass of a continuous character formed by heavy elements (Figure 2.7).

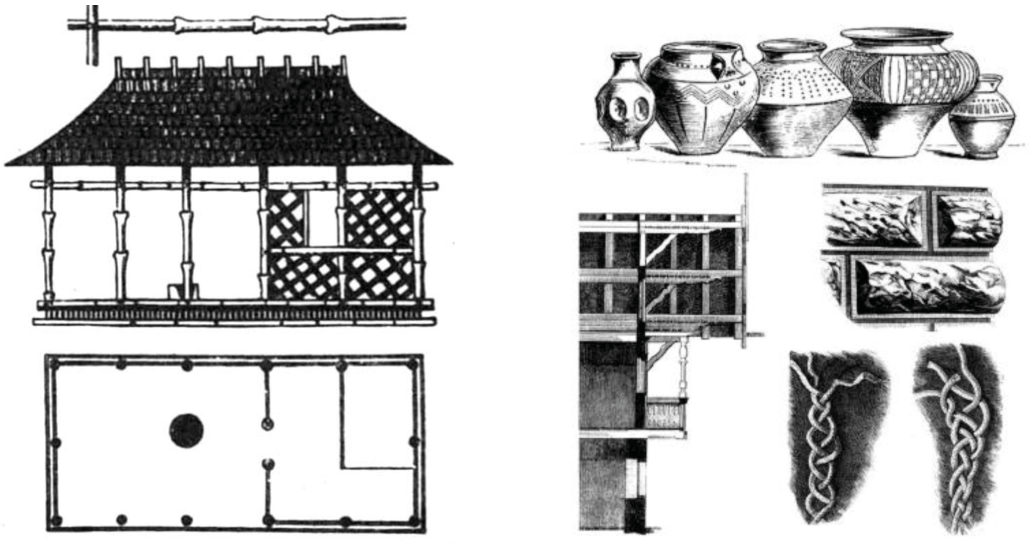


Figure 2.7: Gottfried Semper. a) Indian hut from Trinidad on display at the Great Exhibition, 1851, as archetype for the four elements of architecture; b) the four crafts associated with each element: pottery, wood working, stonecutting and weaving.

Despite a later evolution of the concept of tectonics,[3] Semper's initial definition of tectonics includes the relevance of the material and the processes of its transformation into expressive forms. In effect, for Semper, tectonics is a *"product of human craftsmanship"*, not only as a means to an end, but particularly when it *"reveals a conscious attempt by the artisan to express cosmic order and laws in shaping the material."* (Hartoonian and Frampton, 1997). Furthermore, for Semper the elevation of the simple material to the work of art is only possible *"through a judicious and appropriate treatment of the materials, according to their properties and taking these properties into account when creating the form"*, creating a link between materials, process and architectural form (Semper, 1989).

At the end of the second half of the 20th century, historian Kenneth Frampton continued to develop the concept of tectonics in the modern context, as an opposition to the scenographic character of postmodern architecture (Frampton, 1990). Starting from the concepts of Botticher and Semper and the etymological analysis, mentioned above, Frampton focuses on the study of the works of Frank Lloyd Wright, Auguste Perret, Mies van der Rohe, Louis Khan, Jorn Utzon, Carlos Scarpa, demonstrating the possibility of using the theme of tectonics as a guideline to interpret works of apparently distant characters on the same common plane. As such, Frampton analyses the history of contemporary architecture in its approach to form and space, through successive material, technical and poetic logics of construction.

As mentioned before, regardless of the complexity inherent to the concept of tectonics and the multiplicity of levels of meaning present in the works of the mentioned authors, it is possible to infer recurring topics. Material properties, transformation processes and technologies, construction, structure, shape, form, art. We can thus summarise and consider that the way in which materials, processes and the built spatial form are articulated is central to the tectonic character of a work of architecture. In this regard, in the article "Architecture – Form and Technique", Karl Christiansen defines Form, Technique and Material as axioms of architectural production, concluding that in the absence of a relationship between them, a work cannot be considered as architecture (Pedersen, 2013).

Although certainly reductive, in this thesis we will use the broad definition of tectonics present in Heidegger and Frampton's etymological reading, resulting from the term *téchne* as "bringing-forth" or creating as an expression of the knowledge and transforming skills related to a particular material into a final form. Within this notion of tectonics, and within the scope of this dissertation, focused on a material, we are therefore specifically interested in concentrating on

[3] Semper refines his notion of tectonics to include only the assemblage of discontinuous elements, separating the tectonic from the stereotomic, the linear structure from the continuous volumetric mass.

the coherence (or lack-thereof) between these three tectonic dimensions: **form**, **techniques** and **materials**, and in the expression of such relations in the production of architecture.

2.2.2 Form, surface and composition

Regarding the previously mentioned three tectonic dimensions of form, technique and material, concrete expressem the in a particular fashion, containing a high level of variability in each of them. Concrete can achieve diverse forms, requiring different techniques for its construction and its own materiality is, as discussed before, variable. This fact enabled throughout the history of architecture, different tectonic expressions in this material. Works such as the Sports Palace by Pier Luigi Nervi, the chapel at Cuernavaca by Félix Candela or the church at Ronchamp by Le Corbusier can demonstrate the broad spectrum of possible approaches to the themes of form, technique and materiality in concrete construction. From precast modular systems, to continuous thin shells, to monolithic structures.

But although the concept of form is clear as the overall shape of a concrete work, the general concepts of technique and material can be difficult to express. How does technique and materiality define themselves in concrete architecture? As such, we propose a subtle redefining of the triad of form, technique and material for the specific context of concrete architecture, changing them into form, surface and composition, thus creating the conceptual framework that will be used throughout this dissertation (Figure 2.8). Form being the shape of the created work, surface the medium through which technique is mostly expressed and composition is where the materiality of concrete is defined. Each term is more concretely addressed below:

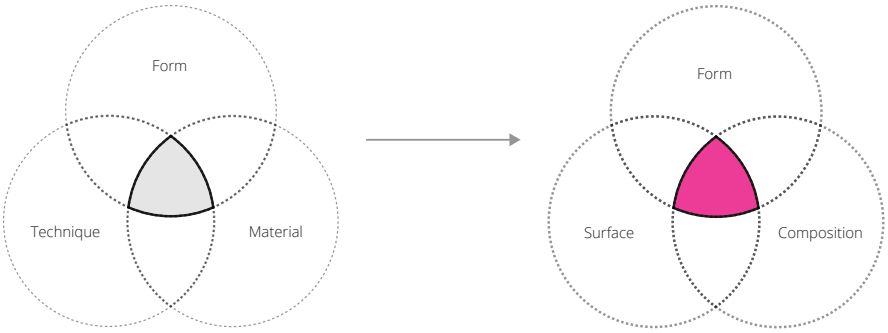


Figure 2.8: General tectonic dimensions in architecture and their translation into a specific material language of concrete.

- **Form.** In this context, form is understood as the general configuration of the work or elements built in concrete, regardless of its structural nature. Monolithic in character or composed of discrete elements. More specifically, form is characterized by the geometric or volumetric description of surfaces built in concrete. As discussed earlier, unlike materials such as stone or wood, concrete, being a mouldable material, does not have a specific form. It has, however, the possibility of assuming any form. Therefore, form will be of particular relevance in the production of complex geometries and non-standard and variable curvatures.

- **Technique - Surface.** A large part of the character of concrete architecture depends on the construction of the formwork. However, this fundamental element on which a large part of the construction technique is based, disappears in the finished work. Nevertheless, marks of this process remain on the apparent concrete surfaces, which are recurrently used as vehicles of tectonic expression, irrespective of any underlying form. Construction marks and formwork materials, concreting joints, fixing holes and surface treatments are elements that convey a second level of meaning, directly related to the techniques and technologies used in the concrete transformation process. In this sense, it is in the concrete surface, in its textural, haptic and visual qualities, that the technique inherent to concrete construction is expressed, as a symbolic narrative of its process or as the result of a later purposeful intervention.

- **Material - Composition.** When considering a particular material, one must also consider a set of properties that are inherent to it. However, unlike other materials with a traditionally fixed composition, one of the main characteristics of concrete is its aggregate nature, dependent on the amalgamation of several raw materials. This aspect dictates the possibility of exploring and controlling its composition and, consequently, all its material properties. From the most common changes to its mechanical strength, elasticity or color, to more sophisticated properties such as sensitivity to light or moisture (Cohen et al., 2006). Composition is thus necessarily a design consideration, not only for its functional purpose, but also for the expressive possibilities it provides. The specific materiality of concrete is defined in its composition, by constraining or considerably enhancing both the production of the form and the character of its surface.

This focus on form, surface and composition, as specific tectonic elements of concrete architecture, will enable an understanding on how new technological approaches can represent moments of continuity or discontinuity with the past. It is our belief that the use of digital fabrication tools has the ability to affect and work together with each of these elements, continuing and

expanding traditional tectonic relationships in concrete architecture. In the following section, we will discuss how these three dimensions were explored in traditional concrete architecture.

2.3 Concrete in traditional architecture

As a comparative basis for the remaining dissertation, this section demonstrates how the tectonic concepts of form, surface and composition were interpreted in traditional, pre-computational, concrete architecture. Through this analysis, we are able to more clearly infer the expansion of these concepts in the digital context, as well as find key topics to explore using digital fabrication tools in the practical part of this dissertation. To this effect, a survey of reference works (Figure 2.9) was conducted, where each of the 3 themes was explored. In particular, to illustrate:

- Different categories of geometrical forms typically built with traditional concrete construction technologies and the different building strategies employed.
- Different approaches to the expression of apparent concrete surfaces.
- How material composition was explored for either constructive or architectural motivations.



Figure 2.9: Reference works in concrete in the 20th Century, focusing on forms, surfaces and compositions: a) Zeiss Planetarium; b) Zarzuela Hippodrome; c) Palmira Chapel; d) Sicli Factory; e) Sports Palace; f) Philips Pavilion; g) Centro de Estudios Hidrográficos del CEDEX; h) American Cement Building; i) Unity Temple; j) Musée National des Travaux Publics; k) Unité d'Habitation; l) Jonas Salk Institute; m) Yale Art and Architecture Center; n) Everson Museum (detail); o) La Moraleja House; p) Municipal Theatre; q) Rome Pantheon; r) Musée National des Travaux Publics (detail); s) Naval Academy of Leghorn; t) Everson Museum.

2.3.1 Form

The first prototypes in reinforced concrete, namely the conical vases and the curvilinear boat hull of Monier and Lambot, in 1848-50, were early demonstrations of the possibility to materialize curved and complex shapes in this material. Likewise, at the beginning of the following century, a set of formally expressive images of industrial buildings in concrete were published by Walter Gropius (Gropius, 1913) and reused in Le Corbusier's manifesto (Corbusier, 2013), extolling the purity of its forms and illustrating this initial link between concrete, the production of complex geometries and the appropriation of their expressiveness in architecture.

Although the purity of the forms shown by Le Corbusier has endured in architectural discourse, early efforts were also made to explore the formal limits of this material besides the simplicity of regular platonic solids. Therefore, it becomes relevant to understand which specific forms were explored and which strategies were used to build them.

In this context, we identified two main archetypes, which represented the most relevant explorations of complex curved shapes in early 20th century concrete architecture, separating between continuous and discontinuous logics of design:

- Monolithic thin shells of curved geometry
- Precast complex modular elements

The examples presented here demonstrate the formal possibilities of concrete architecture, as well as the traditional processes of its construction and its inherent technological limitations, suggesting possible strategies for innovation through contemporary processes.

Monolithic thin shells of curved geometry

The first modern building usually identified with this typology was the 30mm thick hemispherical roof shell of the Zeiss Planetarium built in Jena, in 1926 (Kurrer and Ramm, 2012). A period of strong exploration followed from the early 1930s, marked by the works of Eduardo Torroja, Felix Candela and Heinz Isler, demonstrating the ability of concrete to assume self-supporting, continuous surfaces of considerably reduced thickness, both structurally efficient and aesthetically appealing through the use of non-standard geometries.

Structurally, examples of this type of buildings are characterized by greater mechanical efficiency, attributing the increased stability to their geometric configuration and not to an increase in mass, supporting their own weight with a minimal amount of material, compared to other types of construction structures (Tomas and Martí, 2010).

The curved geometries displayed in this type of structures were in a first instance, based on the manipulation and combination of revolution or ruled surfaces, of single and double curvature. In general, shapes describable by the rules of analytic geometry. The possibility of a mathematical description of these forms, endowed them with a clarity of design, structural analysis and fundamentally, ease of construction. Thus there is a considerable range of such built forms, starting from the simplest spherical and cylindrical domes to conoids, hyperboloids and hyperbolic paraboloids.

One of the most notable cases of the exploration of these forms can be found in the work of Felix Candela, having designed almost exclusively with hyperbolic paraboloid surfaces, transformed, combined and adapted to a wide range of architectural programs (Garlock and Billington, 2008). The chapel at Lomas de Cuernavaca (Figure 2.10 a)) is a clear example of this approach, being designed from the sectioning of a single hyperbolic paraboloid surface, 30 meters long and 24 meters high, built with an average thickness of 4 cm (Basterra Otero, 2001).

The construction of this type of curved concrete surfaces traditionally depended on the use of wooden formwork, built from discontinuous elements. Its ruled nature enabled the description of the necessary formwork surface through linear elements (beams and boards), following the same geometric rules as the intended surface. This aspect drastically simplified the construction of the formwork, making the complex curved designs feasible, without geometric rationaliza-

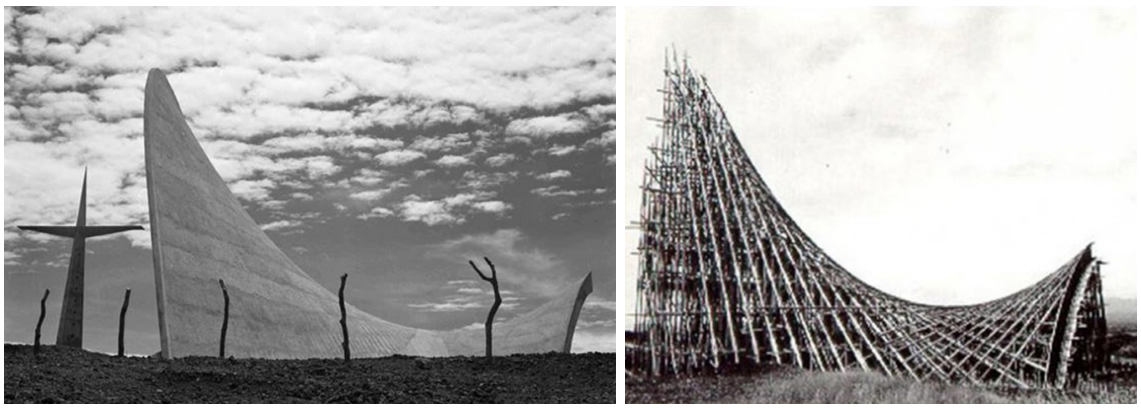


Figure 2.10: Chapel in Lomas de Cuernavaca, Felix Candela, 1959. a) cast concrete surface; b) wood formwork construction process.

tion or technologically advanced manufacturing processes (Figure 2.10 b)).

A step forward in terms of formal complexity, was taken by the Swiss engineer, Heinz Isler. Unlike Candela's works, Isler explored non-mathematically describable forms, using experimental methods of form-finding, based on the exploration of physical models (Candela, 2008). The resulting shapes assumed considerably greater geometric complexity than ruled surfaces, being mostly variations of non-ruled, double-curvature forms (Figure 2.11 a)).

His most emblematic works were designed using models built from membranes distorted by gravity, resulting in perfect funicular structures which when inverted, resulted in self-supporting geometries, optimized for compression forces. These physical prototypes were later used as models for the calculation and design of the final structures (Chilton, 2010). One of the most emblematic examples of this process can be found in the Sicli Factory (Geneva, 1969). This work highlights the possibility of achieving a high degree of formal complexity and expressiveness, with a 100mm thick double curvature shell of asymmetrical shape (Figure 2.11 b)).

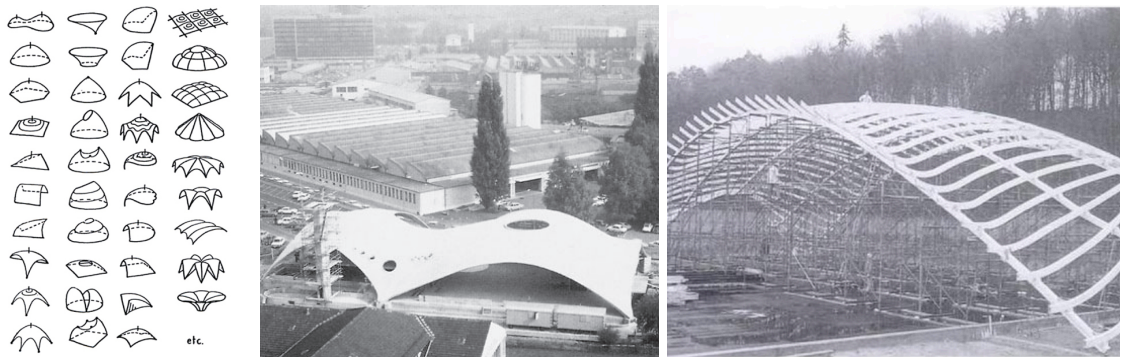


Figure 2.11: a) "New Shapes For Shells", Heinz Isler b) Sicli Factory, Heinz Isler, 1969 c) wood formwork for double curved thin shell structure

Compared with Candela's analytical forms, this type of geometries cannot be described through linear elements. Thus, the construction of Isler's free forms required considerably more complex formwork systems. Such systems were based on the description of the desired surfaces through the use of bidirectional sections of variable curvature. Using more advanced wood processing technologies, these sections were built in laminated wood and covered by thin, bendable wooden planks or panels, interpolating the designed geometry (Chilton and Isler, 2000) and used as formwork surfaces (Figure 2.11 c)).

The design of this type of structures began to decline from the 1970s onwards, with most of this type of constructions being built between 1950 and 1970 (Figure 2.12). This decline resulted from a multitude of reasons, namely programmatic and spatial adequacy, costs and construc-

tive issues (Rippmann, 2016). In the latter case, this was mostly related to the difficulties of building formwork systems that were necessarily customized, which were gradually replaced by standardized strategies.

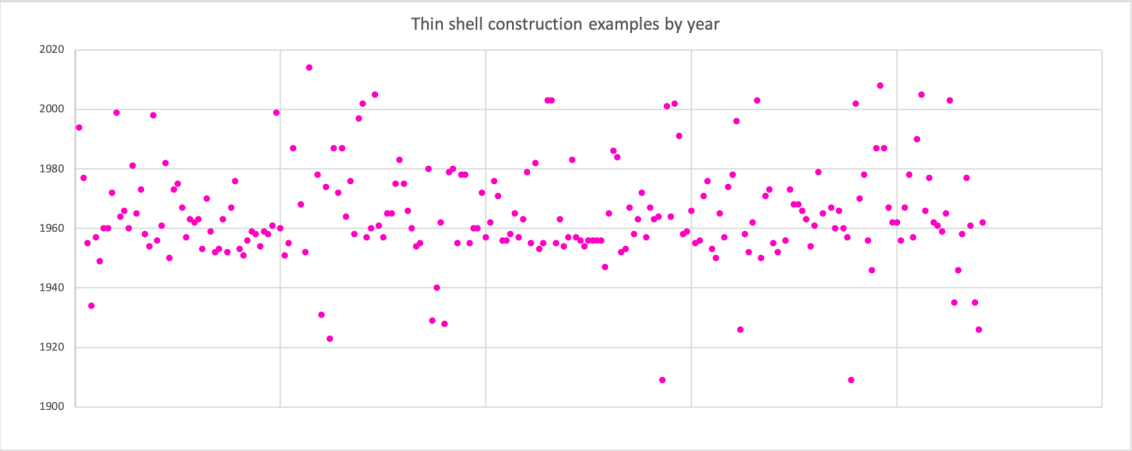


Figure 2.12: Decline of thin shell construction in the last 100 years. Plotting the construction date of 220 examples, sourced from https://structurae.net/.

Precast complex modular elements

Although many examples of formal explorations of concrete architecture are focused in the design of complex geometries through continuous surfaces cast in-situ, other approaches were found, based on the description of surfaces through their subdivision into discrete prefabricated elements. Such elements assumed either structural or cladding roles, with complex shapes being explored in both the geometry of the elements themselves and in the general shapes they described.

Between the 1940s and 1960s, Pier Luigi Nervi carried out a series of large-scale works, exploring a constructive logic considerably different from those adopted until then, based on the prefabrication of modular components. In some cases, these components assumed the roles of structural elements while in others, they were used as superficial lost formwork for complex ribbed structures. The method developed by Nervi and defined by Iori and Poretti as "structural prefabrication" (Iori and Poretti, 2005) started from the subdivision of the design geometry into discrete units of convenient dimensions, prefabricated and assembled on site, becoming part of the finished structure after being consolidated with a final layer of concrete. Due to economic,

temporal, technological and material constraints,[4] these components were limited in variability and geometric complexity, with Nervi using mostly 2 types of elements with different dimensions, in the majority of his works.

Although Nervi showed a preference for the construction of relatively symmetrical curved shapes (spherical and cylindrical domes), facilitating their modular subdivision, this technique allowed for the construction of variations of these geometries, with considerably more complex designs. Furthermore, although the geometry of the *ferrocement* elements used by Nervi was not exceptionally complex (rhomboid and "V" shaped elements), their articulation allowed for an appearance of considerable geometric complexity. This was evident in the curved roof of the Exhibition Hall in Turin (1949) or in the recurring ribbed designs such as the roof of the Sports Palace in Rome (1958) (Figure 2.13), built from 1296 rhomboid elements of only 12 different dimensions (Iori and Poretti, 2005).

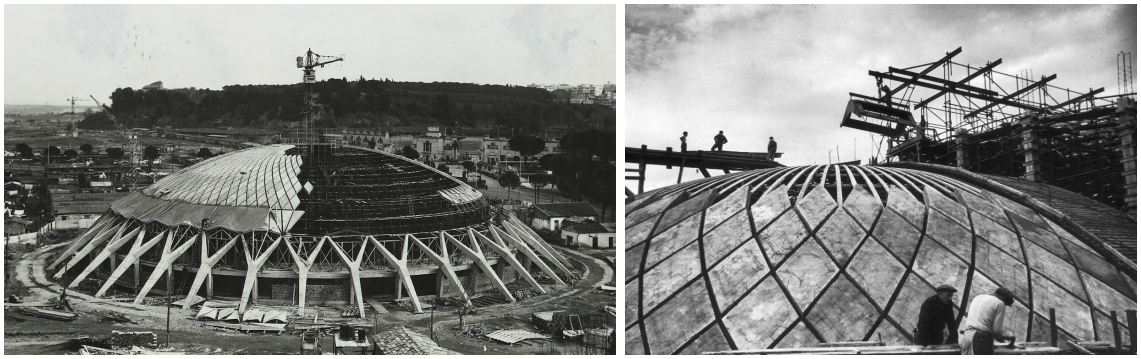


Figure 2.13: Sports Hall, Pier Luigi Nervi, 1958; overall structure and detail of ferrocement rhomboid elements before casting.

Although Nervi's methods resulted in high labor costs, it is evident in these cases that prefabrication enabled a considerable optimisation of the construction process. Namely, in the consumption of materials, in the production of waste and in the construction time, with the clear inconvenience of geometric repetition, and consequent limitation of the possible formal lexicon.

A second relevant example on this subject is the construction of the Philips Pavilion for the Brussels World Exhibition (1958) by Le Corbusier and Iannis Xenakis. The design explored the

[4] Iori and Poretti mention the particular situation of Italy at the outbreak of the 2nd World War as a catalyst for Nervi's rational prefabrication logic, namely, a great scarcity of materials (mainly iron) that prevented its use in construction and, at the same time, an availability of labor. Interestingly, we find ourselves today in a similar situation, where, on the one hand, for ecological and economic reasons it is important to consider the optimization of material resources and, on the other hand, robotic technologies allow a reduction in labor-related costs.

creation of a continuous curved interior space to house the *"Poème Eletronique"* multimedia installation. The plan featured two principal curved lines, creating an interior perimeter which was enclosed through the intersection of a set of hyperbolic paraboloid surfaces defining the expressive exterior form of the building (Figure 2.14). Despite its ruled geometry, the variability of the surfaces in question, as well as their thickness and high degree of curvature, made their construction unpractical through traditional wood formwork processes and an innovative sand formwork system was used.[5]

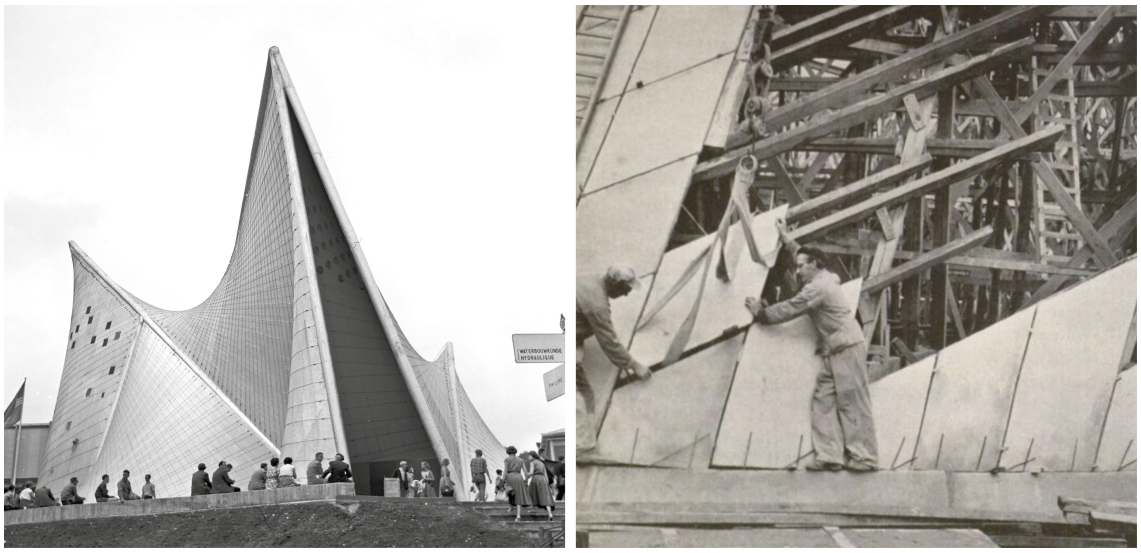


Figure 2.14: Philips Pavilion, Le Corbusier, Iannis Xenaquis, 1958. a) finished precast concrete surface elements; b) detail of precast panels in facade surface (Xenakis et al., 1958)

The Philips pavilion is an early example of the construction of curved and geometrically complex shapes in concrete through its subdivision into discrete modular elements of variable geometry. The strategy found for the construction of its concrete surfaces demonstrated the need for sufficiently flexible and economically viable mould construction methodologies to overcome the standardisation of elements normally associated with prefabrication.

Regarding the use of modular elements in concrete architecture, it is possible to find other examples where one moves from an exploration of the general shape of a curved surface through discrete elements, to a focus on the geometry of the elements themselves. As a rule of thumb, it can be said that the examples where the boldest formal explorations are found are simultaneously those in which there is a greater repetition of modular elements. Cases such as the customised system of prestressed beams developed by Miguel Fisac termed "huesos" (Figure 2.15

[5] More information regarding this fabrication process is presented in Chapter 4 - Revisiting the Philips Pavilion.

a)) or the sculptural elements of the facade of the American Cement Building (DMJM, 1964) (Figure 2.15 a)) or the US Embassy in Dublin (John Johansen, 1964) (Figure 2.15 c)), exemplify not only the possibilities of prefabricating complex shapes in concrete, but also the necessary repetition that traditionally accompanied these strategies of formal exploration.



Figure 2.15: Examples of precast modular systems: a) one of the "huesos" designs by Miguel Fisac, b) structural facade elements from the American Cement Building, 1964, c) modular facade system for the US Embassy in Ireland, by John Johansen, 1964.

2.3.2 Surface

Although the previous works showed implicit qualities in relation to the concrete surfaces (when exposed), the most evident consideration would have been with their formal expression. Nevertheless, the exposed concrete surface has traditionally been an important and varied source of architectural expression. Having clearly reemerged in the second half of the 20th century as an architectural interest, Réjean Légault mentions the apparent surfaces of Frank Lloyd Wright's Unity Church (1908) as well as Perret's initial concerns with the quality of concrete surfaces as relevant precedents (Legault, 2006).

Starting from the experiences with Corbusier's "béton brut de decofrage", architects such as L. Kahn and P. Rudolph, developed several works where the expression of the textural qualities of the apparent concrete surfaces was considered as a fundamental part of the project, regardless of any underlying form. Within this theme, we identify two main sources of expression, considering wether surface textures were emerging results from casting processes or forced artificial textural effects:

- Casting traces
- Manual or mechanic post processing

The first relates to the exploration of imprinted traces on exposed concrete surfaces, resulting from the different stages the construction process, most notably, traces of formwork elements. The second refers to processes of direct transformation concrete surfaces after they have been built, using different mechanical or manual processes to achieve different textural qualities.

Casting Traces

As mentioned, the design and construction of the formwork is one of the principal phases of the concrete construction process. Not only it is responsible for constraining its form, but it is in the interaction between the mould and the concrete mixture that the qualities of its finished surface are defined. Consequently, several architects explored the aesthetic possibilities inherent to the use of different formwork strategies and materials in defining apparent textured concrete surfaces.

In works such as the Unité d'Habitation in Marseille (Le Corbusier, 1952), and the Jonas Salk Institute (Louis Kahn, 1965), exposed concrete surfaces exhibit textures with different expressive qualities, directly resulting from the process, materials and technologies of construction of the respective moulds.

Traditional wooden formwork systems, such as the ones used in the Unité d'Habitation, generally resulted in uneven surfaces, with strong traces of the formwork elements. In this case, the texture of the individual wooden planks is evident, as well as their direction and junction in subsections, particularly in the case of the lower monolithic pillars and roof structures (Figure 2.16 a)). Corbusier refers to the presentation of the material in its "raw" state and to a humanization of the material and elevation of human work, through the exhibition of its flaws (Boesiger, 2015). Nevertheless, we are interested, however, in the important role of the construction technology and how its intricacies seep into the exposed surfaces of concrete.

Naturally, this idea of material expression through the qualities of exposed surfaces followed subsequent advances in formwork technologies. From the second half of the 20th century onwards, new formwork systems, such as the use of large plywood panels, encouraged the exploration of concrete surfaces with an exceptionally smooth finishing quality.

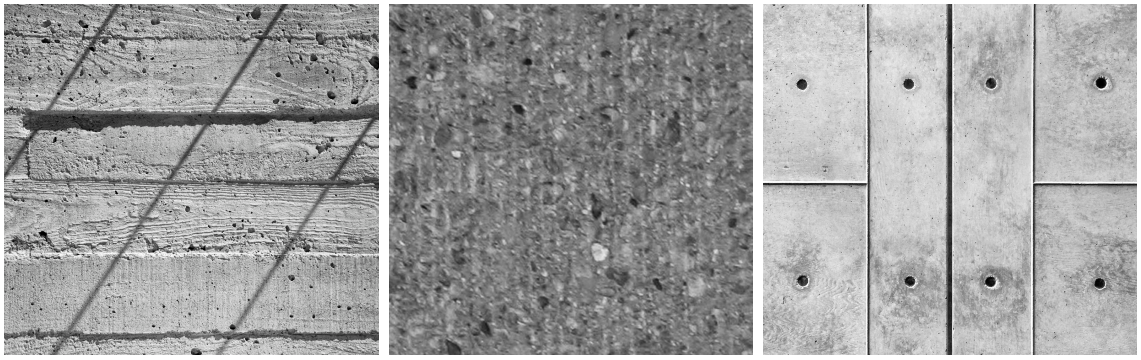


Figure 2.16: Details of exposed concrete surfaces in: a) Unité d'Habitation de Marseille, Le Corbusier, 1952; b) Musée National des Travaux Publics, Auguste Perret, 1946; c) Jonas Salk Institute, Louis Kahn, 1965.

Taking advantage of this technology, Louis Kahn in the Jonas Salk Institute focuses on controlling the concrete construction process, meticulously exploring and highlighting its surface traces. From the stereotomic design of the panels, to the cutting of their joints producing high reliefs on the surface, to the precise positioning of the anchor holes and the casting process. Kahn produces an exposed concrete surface that not only narrates its execution process, but also elevates it to the main subject of the design (Figure 2.16 c)).

Other relevant examples also exist that went beyond the exploration of traditional formwork processes, developing other expressive languages in concrete surfaces. Perhaps one of the most relevant example in this regard was Miguel Fisac's experiments with flexible moulds. In these cases, Fisac explored casting techniques that allowed him to manifest on the surface what he considered to be the true plasticity of concrete, as opposed to a "false texture", provided by wood (Fisac, 2010). To this end, Fisac used a system of smooth polyethylene membranes fixed to rigid structures, as formwork to cast prefabricated elements and in-situ constructions. The active character of this formwork material in relation to the weight of the concrete resulted in small-scale controlled deformations, giving rise to highly expressive textures[6]. In works such as La Moraleja (1973) and the Municipal Theater (2000), Fisac demonstrates the possibilities of this system and, more relevantly, the fact that the integration of innovative technological solutions in the concrete creation process can introduce profound changes in the properties of their apparent surfaces (Figure 2.17).

[6] Although these effects could be considered formal aspect, their scale and application in buildings with more traditional geometries, lead us to consider these effects as textural rather than formal.

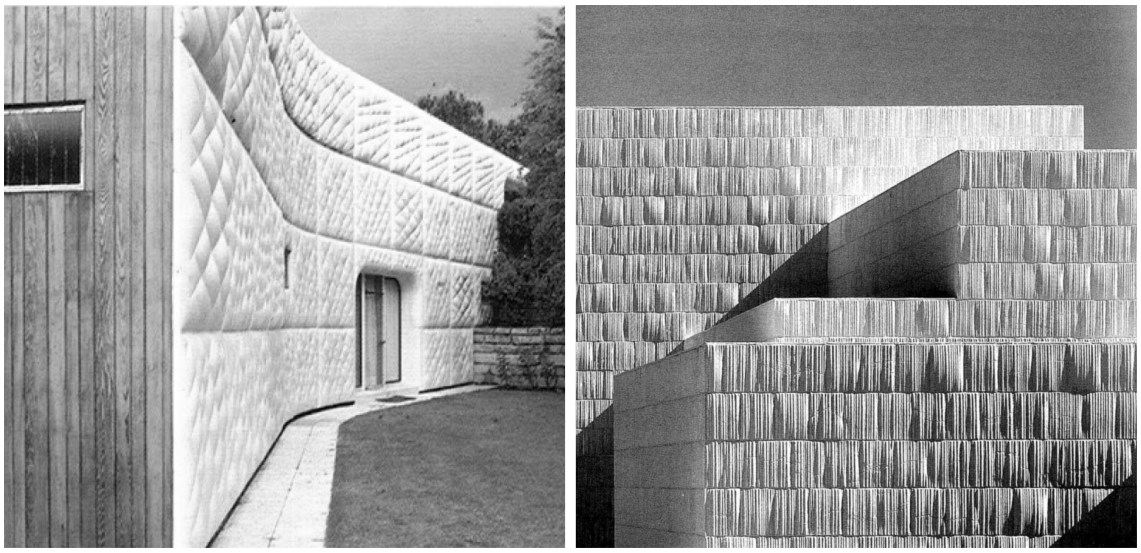


Figure 2.17: Deformed textured surfaces in concrete panels resulting from alternative formwork processes. a) La Moraleja, Miguel Fisac, 1973; b) Municipal Theatre, Miguel Fisac, 2000.

Manual or mechanic post processing

Although most of the concerns with exposed concrete surfaces have historically focused on controlling the first stages of the construction process, with the material in its liquid state, other approaches focused on the transformation of its surface after solidification. These approaches, which we refer as post-processing, were based on manual, mechanical or chemical treatments on the finished surfaces, polishing or removing its superficial layers, in a controlled manner, either partially or completely (Deplazes, 2005).

Although there are early examples of post processed exposed concrete surfaces from the beginning of the 20th century, they are mostly in an attempt to approximate the aesthetics of stone (Collins et al., 2004). More relevant examples can be found in the second half of the 20th century. American architects such as Paul Rudolph and I.M. Pei., from the 1960s onwards, developed several works where the exposed concrete skin was treated a posteriori, exploring different textural expressions. In works such as the Art and Architecture Building (Paul Rudolph, 1963) (Figure 2.18a)) and the Everson Museum (IM Pei, 1968) (Figure 2.18b)) the surface textures ranged from rough to smooth expressions exploring light/shadow contrasts through vertical and diagonal patterns with different scales, finishes and depths.

Forty refers to this type of expressions as a reaction to the inadequate ageing of the exposed concrete surfaces, visible in experiments of the previous decade. However, more relevant in these cases seems to be the rejection of the formwork language, giving primacy to the expression of a unified texture. This aspect is evident in the monolithic and uniform facades of the Everson Museum (Figure 2.19), where few traces of the casting process survive. It can be therefore understood, as a desire to express a texture, independent of the casting process and the formwork technologies used, focused on the homogeneous nature of the material, nevertheless resulting in interesting visual and haptic qualities. Although this type of experiences diminished in the following decades, favouring smooth concrete surfaces, the notion of an expression of exposed concrete remained present as a transversal topic to architecture in this material.

From this scenario and the examples presented, it is possible to extract the historical relevance of controlling the concrete construction process and its respective actors as a means to obtain expressive concrete surfaces. In Botticher's tectonic context, these elements could be described as a second layer of meaning which, when arising from a logical process, in the context of the material, acquires a tectonic unity that is otherwise lost. In this way, it can be inferred that changes in the concreting process, namely with the introduction of new transformation technologies and digital production strategies, have the potential to generate new material qualities.

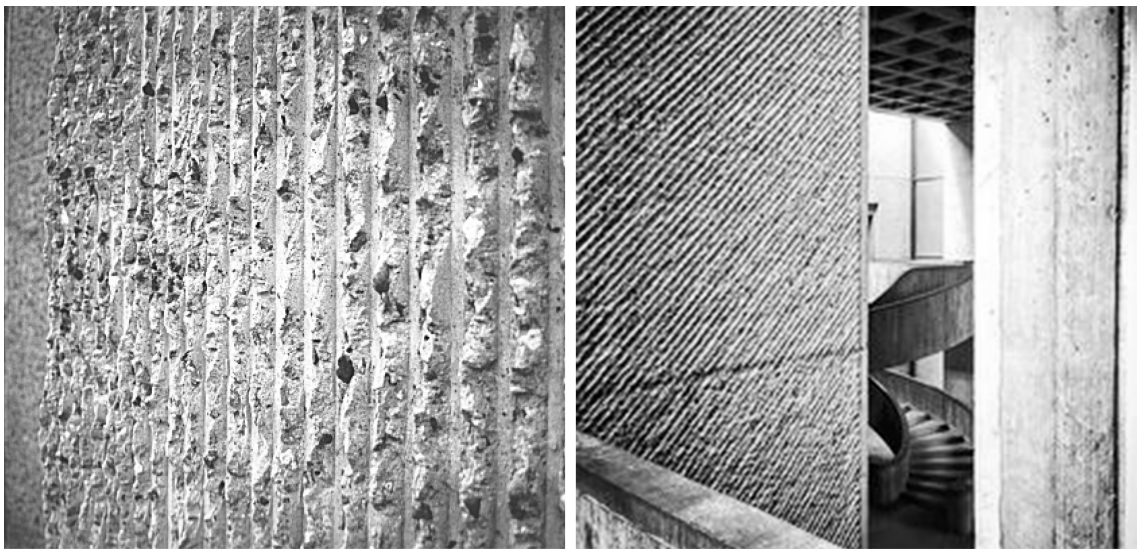


Figure 2.18: Detail of post-processed exposed concrete textures. a) Yale Art and Architecture Building, Paul Rudolph, 1963; b) Everson Museum, I.M. Pei, 1968.

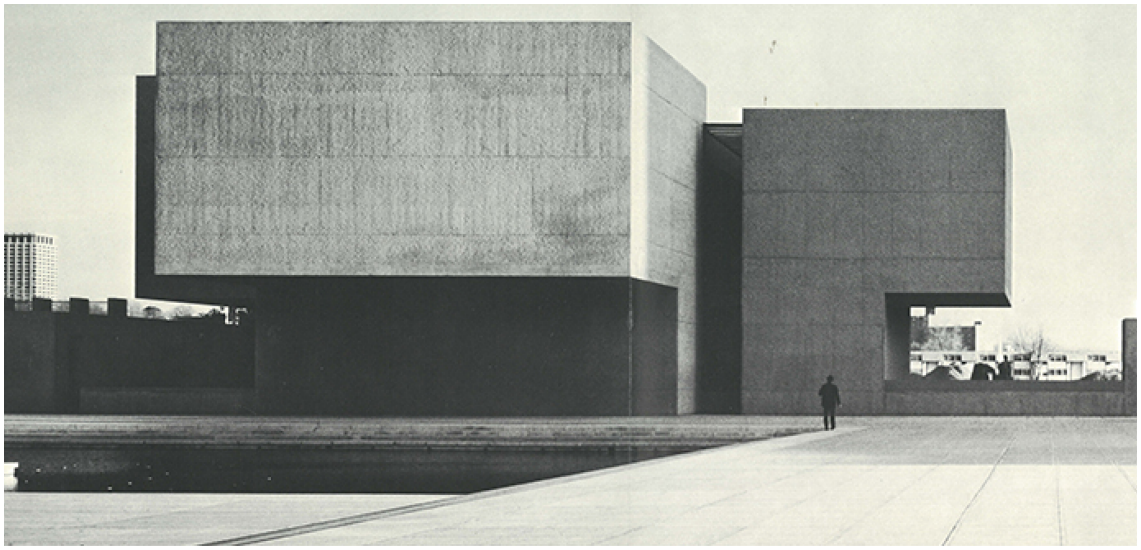


Figure 2.19: Everson Museum, I.M. Pei, 1968.

2.3.3 Composition

Considering the previous examples, the existing literature generally focuses on aspects related to the overall form and textural qualities of exposed concrete surfaces, as the main architectural considerations. However, a considerable part of these two dimensions depends on a particular attention to the material composition of concrete. This fact in many cases places this third dimension as a consequence of the needs established by the two previous ones.

Returning to the material genesis of concrete as an artificial material, produced through the association of various raw materials, it is clear that the control of its composition can serve different interests not only of a technical nature, but also of architectural relevance. In this context, the significance of the concept of composition can be shown in examples of these two motivations:

- Performative motivations, related to the behavior and properties of concrete (e.g., mechanical, thermal, acoustic).
- Aesthetic motivations, implying variations in the appearance of concrete surfaces, operated by changes to its constituent elements.

Performative motivations

The Roman Pantheon was completed between 118 and 128 A.D., and is generally regarded as one of the most relevant and impactful concrete buildings in the centuries preceding the modern era. Both because of its scale and the construction techniques used, it is recurrently referred to as the culmination of roman concrete construction (Mark and Hutchinson, 1986). Although its hemispherical geometry is not particularly complex (there are previous examples of similar shapes), there are no precedents of roman concrete constructions at such scale. The Pantheon's 43-meter-diameter dome remained unsurpassed throughout the next millennium, only being significantly outdone after the development of reinforced concrete and the construction of Maxberg's Centennial Hall in 1913, with its 65-meter diameter dome.

In addition to some particular characteristics in the design of the Pantheon's structure[7], the control of the specific composition of the concrete used was a fundamental element in its con-

[7] Two other devices are usually identified: the existence of a set of concentric rings on the outside of the structure and the coffering system on the inside of the vault.

struction. In order to reduce the resulting lateral forces on the structure, an innovative strategy was used, based on the idea of varying the material properties of concrete, becoming lighter as it approaches the top of the dome (Figure 2.20 a)). To this end, different compositions were used, focusing on the use of low-density aggregates (tuff), as well as ceramic amphorae, reducing the weight in a controlled way along the structure (Lancaster, 2005). This material strategy resulted in a reduction of approximately 80% in the existing lateral forces, making it possible to build the spherical geometry of the Pantheon in the desired dimensions. The case of the Pantheon is one of the earliest and most obvious examples of variation and adaptation of material properties to constructive requirements arising from complex architectural solutions.

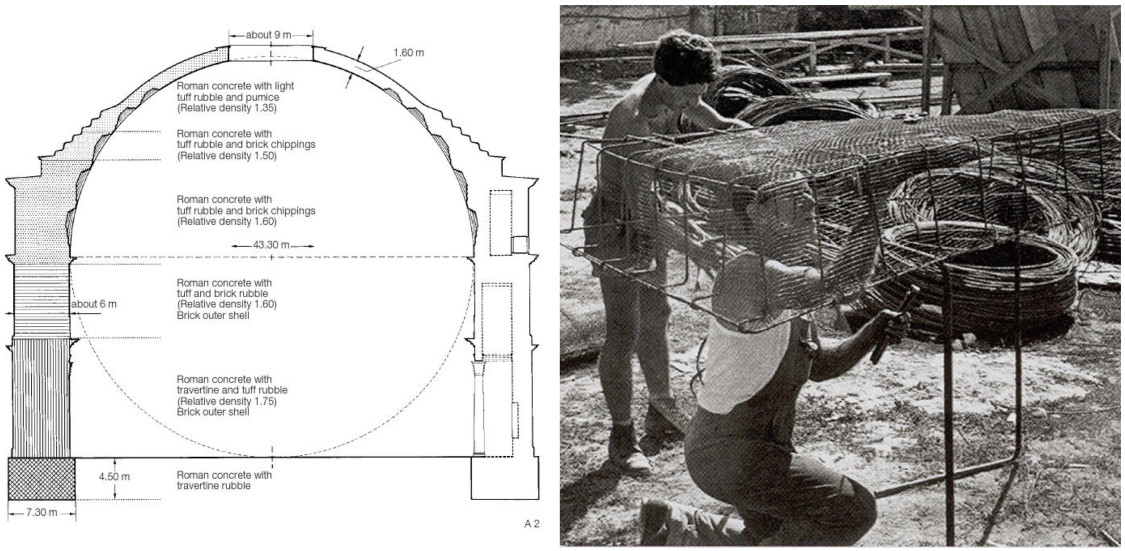


Figure 2.20: Alternative compositions in concrete construction: a) Constructive section of the Roman Panthon, demonstrating the variable composition of the concrete mix used; b) wire reinforcement in ferrocement elements for the Sports Hall in Rome, Pier Luigi Nervi, 1958.

Moving from aggregates to reinforcement it is possible to find distinct examples of altering the performative capabilities of concrete through the exploration of its composition. Returning to the case of Nervi's work, the structural prefabrication process developed in the example of the Sports Palace, largely depended on explorations of reinforcement strategies in the composition of reinforced concrete. In this case, focusing mainly on changes to its elastic behavior in reduced sections.

In response to a shortage of iron, resulting from the socio-economic situation in Italy during the 2nd World War, Nervi sought to optimize concrete construction, exploring the use of low thickness elements to reduce material consumption. For this purpose, he developed a new material from concrete, named *ferrocemento*, by reducing the concentration of aggregates and consider-

ably increasing the density of the metallic reinforcement. This new material, similar to some of Joseph Lambot's previous experiments, would present a new set of properties. Distinguishing it from traditional reinforced concrete, Nervi would describe it as *"a homogeneous material, isotropic, elastic and resistant to compression and tension."* (Iori and Poretti, 2005).

With this material, Nervi was able to build structural elements, such as the curved components for the roof of the swimming pool of the Naval Academy of Leghorn (1947) or for the roof of the Conte Trossi pier (1948) (Nervi, 2016). Or, later, as a simultaneously structural material, lost formwork and interior cladding, in the case of Exhibition Hall B for the Turin fair in 1949 (Figure 2.20 b)).

The control of material properties with performative motivations expanded over the next century, as knowledge regarding the composition and behavior of concrete became an increasingly specialised field. In this sense, there was an avid material exploration, considering changes to all of its main constituent elements - matrix, aggregates, reinforcement and additives. Today, there are several types of concrete with changes to its traditional performance in different properties, specifically programmed to expand the use of this material. Properties such as weight and thermal insulation (lightweight concrete), tensile strength (fibre-reinforced concrete), compressive strength (UHPC - Ultra High Performance Concrete), flowability (SCC - Self Compacting Concrete), opacity (LitraCon/Translucent Concrete) and others.

Aesthetic Motivations

To a large extent, the architectural consequences arising from the first set of motivations presented, articulate directly or indirectly with the concept of form. Changes in the material composition made it possible to produce larger spans, thinner structures or more complex geometries. On the other side of the spectrum, the exploration of concrete composition for aesthetic reasons has traditionally been linked to the concept of surface.

Although the visual and haptic properties of exposed surfaces were often the result of procedural aspects, as described before, they were also intrinsically linked to specific material properties and, therefore, to composition. For instance, the grey color, which has traditionally identified concrete, results from the color of the usual cement-based matrix.

From the outset, considering Perret's first works in exposed concrete, Peter Collins refers the fundamental innovation present in the surface treatment, alluding to his *"careful selection of contrasting aggregates"* to differentiate constructive elements in light and dark tones of the same

material, resulting in an *"elevation of industrial architecture to the highest levels of art"* (Collins et al., 2004).

Color and visual texture (in cases where post-processing was used) were the first and most relevant properties to be explored, adding pigments or choosing materials (sands, aggregates and binders) with specific colors and dimensions to achieve intended expressions.

The Everson Museum, also mentioned in this section, is a clear example of this type of motivation. In this case, the post-processing of the surface not only defines a particular texture, but also reveals, in its internal composition, a specific set of pink aggregates, of local origin (Legault, 2006). In this case, in addition to the visual effect, the control of material composition promotes a connection between the work and the place, as an emerging "earthwork", in the tectonic narrative sustained by Frampton.

2.4 Critical synthesis

The examples presented in the previous section, as well as the concepts they explore, suggest relevant clues to understand the potentials of digital fabrication tools for concrete architecture by addressing the different tectonic dimensions of concrete in traditional cases. However, they also reveal key issues in the materialisation of expressive works in this material.

Despite the apparent freedom expressed in the diversity of approaches, concrete architecture has traditionally been constrained both in terms of design and construction. Although drawing capabilities have evolved considerably in the last decades of the 20th century, particularly with the development of digital design tools, at the construction level, some issues have persisted when materialising formally complex solutions through traditional concrete construction processes. Such difficulties emerged and developed particularly around the limitations of traditional formwork systems, aggravated by the geometric complexity and customisation, intrinsic to non-standard design solutions.

Although the previous decades witnessed a continuous technological development, traditional wood-based formwork materials and systems are still used today. For regular geometries and also for the construction of complex solutions where standardised formwork elements are not possible. In this sense, it is still relevant to identify the main problems and limitations existing in them, which we summarise in the following points:

- **Geometric limitations**. Traditionally available formwork types and materials (wood, laminated wood, fabrics or steel) introduced significant geometric constraints on feasible forms, which were only partially overcome with additional labor, time and construction costs or through the use of geometrical rationalisation strategies.

- **Execution complexity**. The production of this type of structures implied a high level of precision, necessarily involving skilled labor. This was verified not only in the execution of the formwork, but also in the application of reinforcement systems for complex geometries, as well as in the correct definition of the appropriate material (rheological) properties.

- **Production time and costs**. The complexity of construction and the high material consumption (due to the impossibility of reuse in customised solutions) tended to increase execution times and costs, reducing the economic viability and practical applicability of this type of solutions.

- **Sustainability**. The difficulty of reusing formwork systems applied to customised solutions represented considerable material waste, incompatible with situations of scarcity of materials or with growing concerns about the sustainability of construction processes.

The monolithic continuous surfaces by Candela and Isler clearly exemplified these types of limitations and their consequences. In the first case, the ability to build curved geometries from rectilinear formwork elements was exhausted in ruled surfaces, with single or double curvature, and with a limited degree of variability. This was also shown in the case of the Philips Pavilion, which required the use of precast components. Thus, the construction of any non-ruled curvature using these processes resulted in a lack of precision in its description or required adjustments to the designed geometry as well as labour intensive and expensive formwork.

In the case of the works by Heinz Isler, the use of curved laminated wood formwork elements enabled the construction of non-ruled double curvature geometries. However, according to Chilton (Chilton, 2010), the construction complexity involved in this process resulted in the repetition of shapes and the definition of symmetrical geometries (e.g., La Tène Tennis Center, Switzerland, 1983; Sports Center, Bruhl, 1982) (Figure 2.21). Consequently, and taking into account costs and production times, as well as the need for constant specialised labor on-site (Bösiger, 2011), the construction of geometries with greater variability was reserved for exceptional works such as the Sicli Factory.



Figure 2.21: Repetition of forms in concrete thin shell designs by Heinz Isler: a)La Tène Tennis Center, Switzerland, 1983; b)Sports Center, Bruhl, 1982

Other formwork systems, such as the inflatable fabric membranes of the Bini Shell (Roessler and Bini, 1986) and Monolithic Dome systems (South, 1986), addressed the problem of building double-curvature forms, seeking to optimize execution and reuse costs. However, they invariably represented a considerable compromise in terms of possible geometries, being limited to singular domes or associations of such geometries (Figure 2.22).

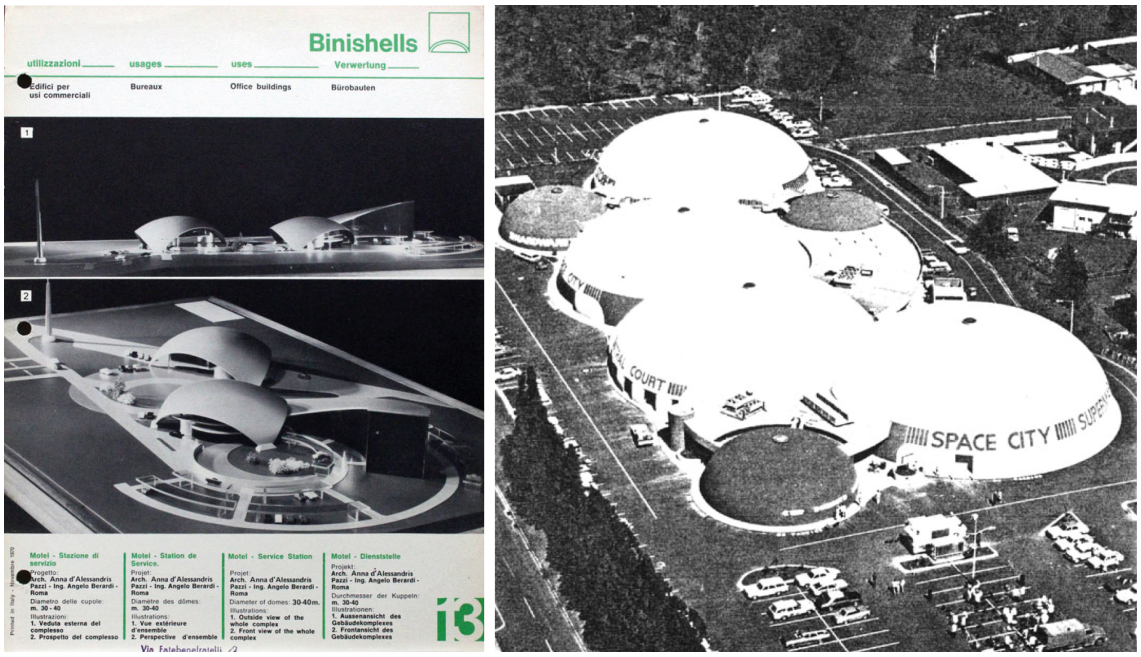


Figure 2.22: Repetition and limited forms in Binishells. a) Binishell catalogue; b)Kallangur Development, Brisbane,1989

These limitations often implied the need for what is referred to as rationalisation strategies on design geometries. In a geometrical context, this concept implies the transition from an initial

geometry to a final, less complex one, according to a specific order[8]. In the architectural and constructive context, Dennis Shelden describes the term rationalisation as a compromise intrinsically linked to construction, defining it as "the resolution of rules of constructibility into project geometry." (Shelden, 2002).

In the specific case of concrete architecture, this notion translates into geometric changes to facilitate the production of complex curved shapes, through the use of flat and standardised formwork elements and materials. In this way, its use involved evident design consequences, significantly increasing the distance between projected intentions and their realisation.

Referring to this issue, in "The Projective Cast", Robert Evans Evans (Evans, 1995) describes the design of the Ronchamp Chapel (Le Corbusier, 1955), which was rationalised at different stages of the design process. Particularly, the concrete elements changed from the sculptural forms of the original models, to ruled forms, more easily describable and buildable with traditional wood formwork systems. A similar example can be found in the Sydney Opera House (Jorn Utzon, 1973). Initially designed as a series of parabolic concrete shells, they were later rationalised into sections of a sphere, making it possible to subdivide the surfaces into equal elements, prefabricated in concrete from identical moulds (Mitchell, 2001) (Figure 2.23).

Although these iterations are sometimes a natural evolution of the design process, their most common motivations are anchored to construction costs and the traditional difficulty of building non-standard solutions (Shelden, 2002). The growing pressure for the design and construction of increasingly complex forms makes it pertinent to develop processes that reduce this distance between the design geometry and the built geometry, in an economically viable way.

Finally, the increasing push towards the construction of complex curved concrete architecture in concrete (Kolarevic, 2004) also raises issues of sustainability, in line with the growing environmental concerns, which should also be considered.

Although a correct analysis of the carbon footprint of this material is a complex topic, as a reference, the production of cement alone, represented 4,1% of the global production of CO_2 in 2014 (Olivier et al., 2015). However, in addition to the direct impact of cement production, much of traditional construction processes in concrete presuppose the use of formwork systems and related labour, that not only represent a considerable part of the construction costs in this material (30-60%) (Johnston, 1997), but also a considerable source of material waste to be taken into account (Llatas, 2011) (Figure 2.24).

[8] This process may involve, for example, the description of curved surfaces by planar elements or the adoption a regular subdivision instead of an irregular one.

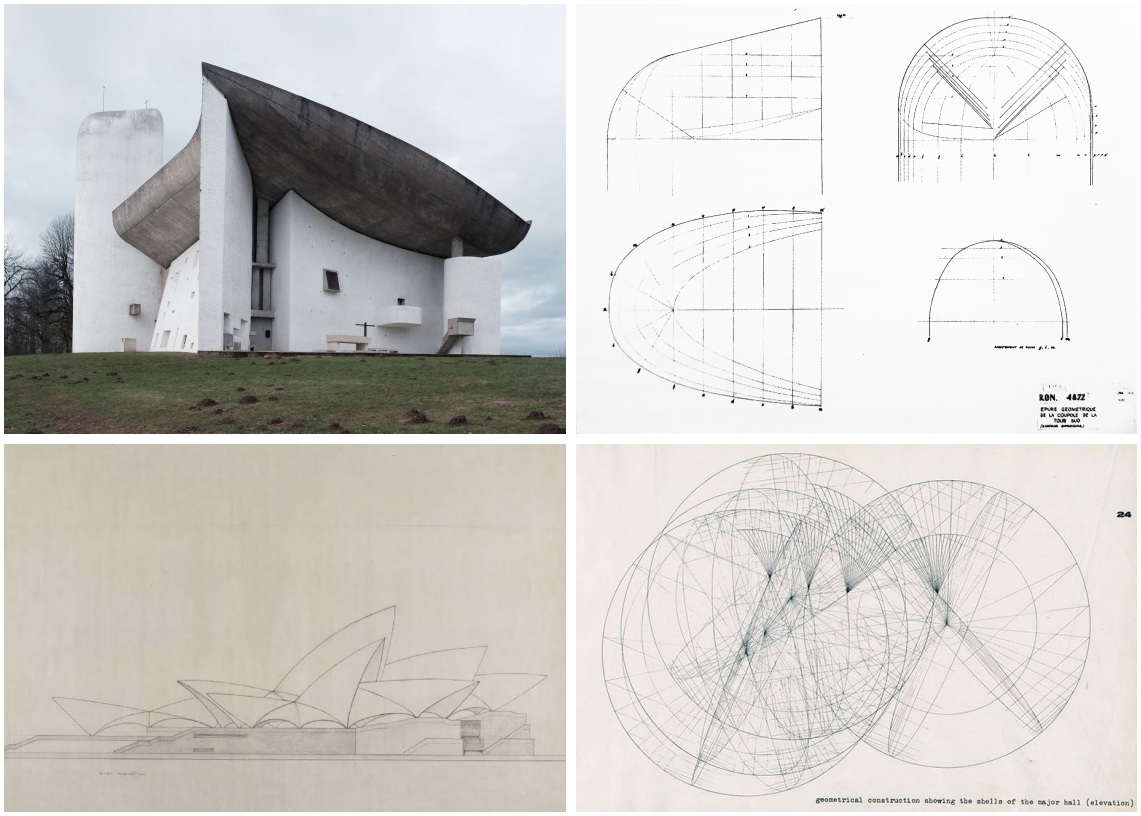


Figure 2.23: Rationalisation process for curved geometries at the Notre Dame du Haut and the Sidney Opera House.

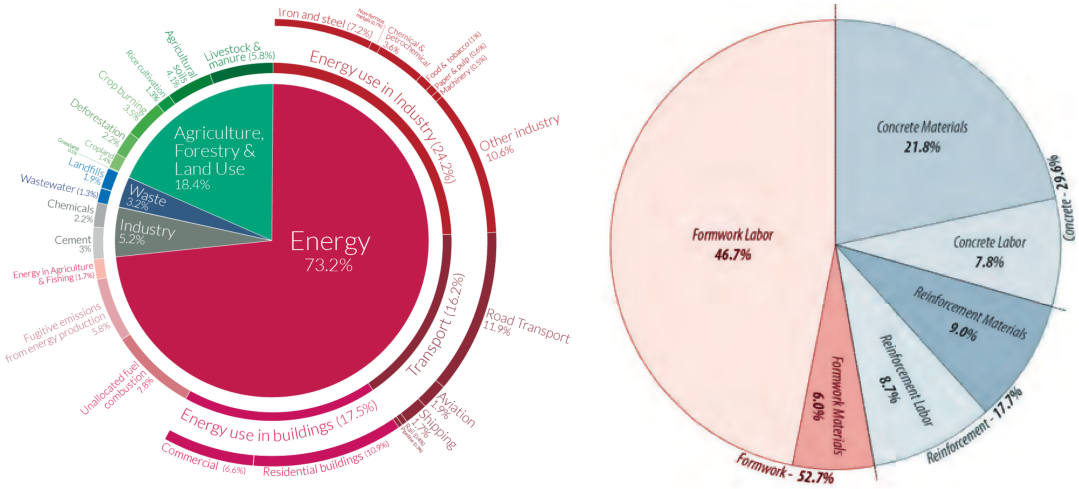


Figure 2.24: Global green house gas emissions by sector ((OurWorldinData, 2016)); average concrete construction cost distribution ((Setareh and Darvas, 2017))

In the construction of the complex geometries highlighted in this chapter, as mentioned in the previous points, the one-off nature of the designs and the low adaptability of the necessary formwork systems tended to result in the production of waste materials, particularly in exhaustible natural resources, such as wood. Moreover, standardisation strategies which could also accomplish reductions in environmental impact through formwork reuse, go in the opposite design direction by in increasing repetition in forms.

Consequently, focusing on the problem of sustainability, it becomes relevant to look for production processes that allow the generation of complex and customised shapes in concrete, while still increasing sustainability potentially by optimising consumption and minimising material waste generation.

A final key topic regarding sustainability but also transversal to all the previous ones, is the issue of monolithic versus prefabricated lightweight concrete architecture. Analysing all the used examples, monolithic continuous concrete surfaces represented most of the traditional cases but also exhibited many of the highlighted features regarding form, surface, and composition. Nevertheless, this construction logic also poses a number of sustainability-related challenges when compared with light prefabricated systems (Pons, 2014). The latter tends to be more sustainable for several reasons, including the need for less material volumes for similar applications, precision of manufacture in controlled conditions leading to less waste and ease of dismantling, reusing or recycling of precast components at the end of their life-cycle.

Chapter 3

Digital Transformations

The examples described in the previous chapter suggest relevant clues for understanding the possibilities that concrete architecture can achieve through the inclusion of digital manufacturing tools. They also revealed the traditional difficulties in materialising complex concrete works that are still present today in a subtancial part of architectural practice.

As previously discussed, the design and materialisation of different formwork strategies has had a considerable impact on the character of concrete architecture since its inception. Its preparation on site, traditionally constitutes a considerable part of the costs in materials, labor and time. In addition to these economic factors, the types of formwork traditionally available to the construction industry often introduce geometric constraints in the creation of complex shapes, which are difficult to overcome without additional costs. Likewise, considerable efforts were made to achieve different expressions in exposed concrete surfaces and to controlling its material composition and behaviour. In any case, there was a set of limitations characteristic of an industry that simultaneously incorporates manufacturing processes and standardisation processes.

In this context, the emergence of manufacturing technologies began to address some of these constraints, proposing new solutions for the materialization of architecture in concrete, as well as revisiting and expanding the concepts of form, texture and composition in the traditions of this material.

In a growing universe of digital fabrication technologies and their application to the specific case of concrete architecture, it becomes relevant to identify and critically analyse the existing examples. As such, this chapter describes and illustrates a classification of the possible and existing types of integration of digital fabrication technologies in the creation of concrete architecture,

to elaborate an analysis of each one. This investigation contributes to guide the relationship between material, technology and architecture in different materialisation strategies, aiming to extract a clear image of the universe of existing processes, their potential and limitations, as well as perspectives for future developments.

3.1 Digital fabrication Processes

The analysis conducted in this chapter considers examples from two different fields: built practice and academic research. The first field testifies to the cases in which methodologies already integrated in the construction industry were used, in works of considerable scale. The second field is characterized by academic experiences of different scales, from prototypes of construction systems to small-scale buildings without a program or with relatively simple programs (eg pavilions). Considering these two fields simultaneously is relevant in this academic context. On one hand, the pace of technological innovation is accelerated, and technologies in early stages of development today quickly pass into practice and those that do not, also present interesting academic ideas. On the other hand, although a true integration of some more exotic techniques by the construction industry is difficult, within the scope of isolated projects, experimental solutions often arise in architectural practice, without the need for precursors.

In addition, it is important to understand not only which technologies are established, but also which technologies are possible. This way, by simultaneously analysing examples from these two fields, it will be possible to understand not only the present and real impact of the use of digital design and fabrication tools in contemporary architecture, but it will also be possible to identify and characterise possible avenues for the development of innovative and architecturally relevant solutions.

Thus, the first step for this analysis is to conduct a survey of examples of concrete works where design and digital fabrication were a relevant factor for the materialisation of the final result. This survey was conducted through a literature review in relevant academic databases. From its analysis, examples of digital fabrication processes were extracted, subdivided and grouped into a classification scheme that defines the spectrum of strategies for integrating digital fabrication technologies into concrete architecture. It will not be the purpose of this investigation, to carry out an exhaustive survey of all the works in question. Nevertheless, the cases referred throughout are considered as examples of specific processes, these processes being the relevant focus of analysis.

The structure used to organize the different strategies found is based on four categories:

1. *Intervention mode*
2. *Transformation logic*
3. *Fabrication strategy*
4. *Application*

The first category of distinction refers to the place of integration of a given technology in the process of building in concrete. Thus, in **1. Intervention mode**, two possibilities are distinguished: **indirect** or **direct** processes. This distinction takes into account the importance that the production of formwork has in the concrete construction industry, as well as in the final expression of this material. The first one is composed of cases where digital fabrication is integrated into this central element of the process, being, in their entirety, digital manufacturing strategies for the creation of formwork systems or moulds for concrete. The second brings together cases that go beyond this traditional condition, focusing on strategies where digital fabrication technologies are directly applied to the material in the initial or final stage of the process. By deposition when it is in its initial liquid state or by transformation if it is in a solid state. In this category, the integration of digital fabrication relegates the role of formwork to the background or eliminates its necessity entirely.

The second category **2. Transformation Logic**, characterises the processes used for its approach to the material, according to the division evident in the technical literature, adapted to the context of digital fabrication in architecture by Rhul (Rhul, 1997) and Kolarevic (Kolarevic, 2004), referring to to three types of processes: **subtractive**, **additive** and **formative**. This differentiation is used here because it defines a direct relationship between technology and material, through the method of its transformation, seeing that as a rule, they imply different material logics that manifest themselves in different architectural applications.

The third category **3. Fabrication Strategy** refers to the specific technological tool or approach used to reach the object in question (formwork system or concrete object). It is a central point of the characterization, bringing together a wide range of tools. However, we consider its inclusion to be relevant due to the fundamental role that the specific digital fabrication tool can have in the character of the concrete work.

The final category **4. Application**, completes the characterization of digital manufacturing processes in concrete, separating the different uses of the same general strategy by specific applications, separating the different types of specific technologies and mould materials in the case of indirect digital manufacturing processes and different typologies of additive technologies, in the case of direct processes. For example, for the same type of logic (indirect), the use of a type of fabrication strategy (2D cutting) can result in different types of formwork systems, depending on the actual technological application (Laser Cutting or 2D Milling) which could even be subsequently separated into different formwork materials (wood, fabric, metal). These will produce different effects in geometry and surface qualities of finished concrete surfaces. Therefore, the use of different materials may imply different design, fabrication and construction strategies with consequences at all levels (form, surface and composition) in the built work. Subcategories from this section were defined not generally, but specifically, according to a best fit logic, considering the studied examples, focusing on finding common themes.

This classification and characterisation process was applied to a list of approximately 100 examples, between the years 1999 and 2020, where digital fabrication systems were central in the construction of prototypes or concrete works. From these, 13 digital fabrication strategies were defined. Seven, corresponding to indirect digital fabrication processes, used for formwork systems and moulds and six for digital fabrication processes applied to the direct fabrication of concrete elements. These strategies are listed below:

Indirect Processes

- 3D milling
- 2D cutting
- 3D cutting
- Dynamic formwork
- Robotic formwork moulding
- 3D printed formwork
- Robotic assembled formwork

Direct Processes

- 3D concrete milling
- 2D concrete cutting
- 3D concrete cutting
- Robotic concrete moulding
- 3D printed concrete
- Robotic Assembly of concrete

These 13 strategies have particular examples subsequently divided into several formwork materials and typologies and different types of concrete printing processes, according to the structure in Figure 3.1. A chronological view of the development of all processes was created by temporally locating each of the studied examples in a procedural timeline, in Figure 3.2. Each concrete digital fabrication strategy is characterised, discussed and classified in the next sections of this chapter.

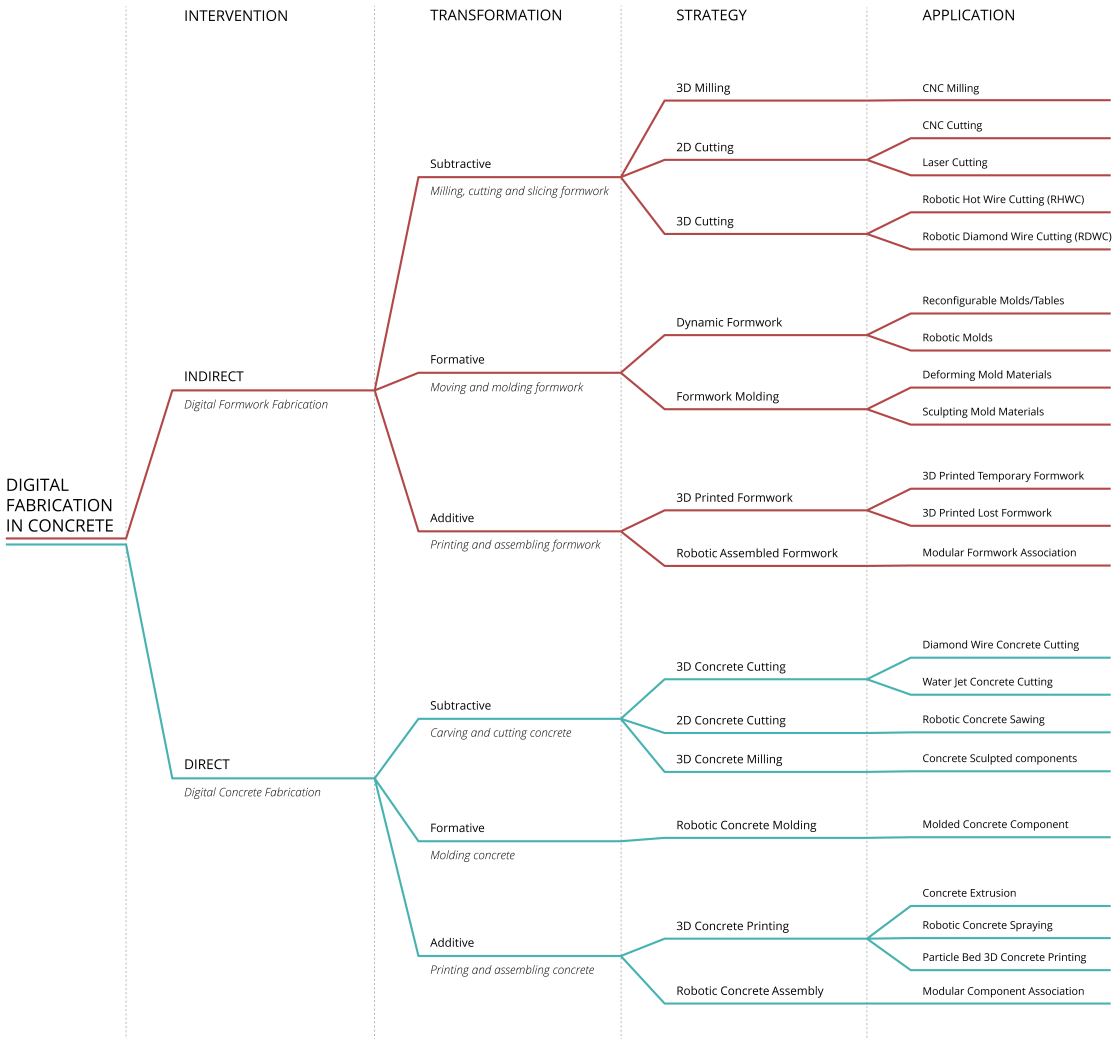
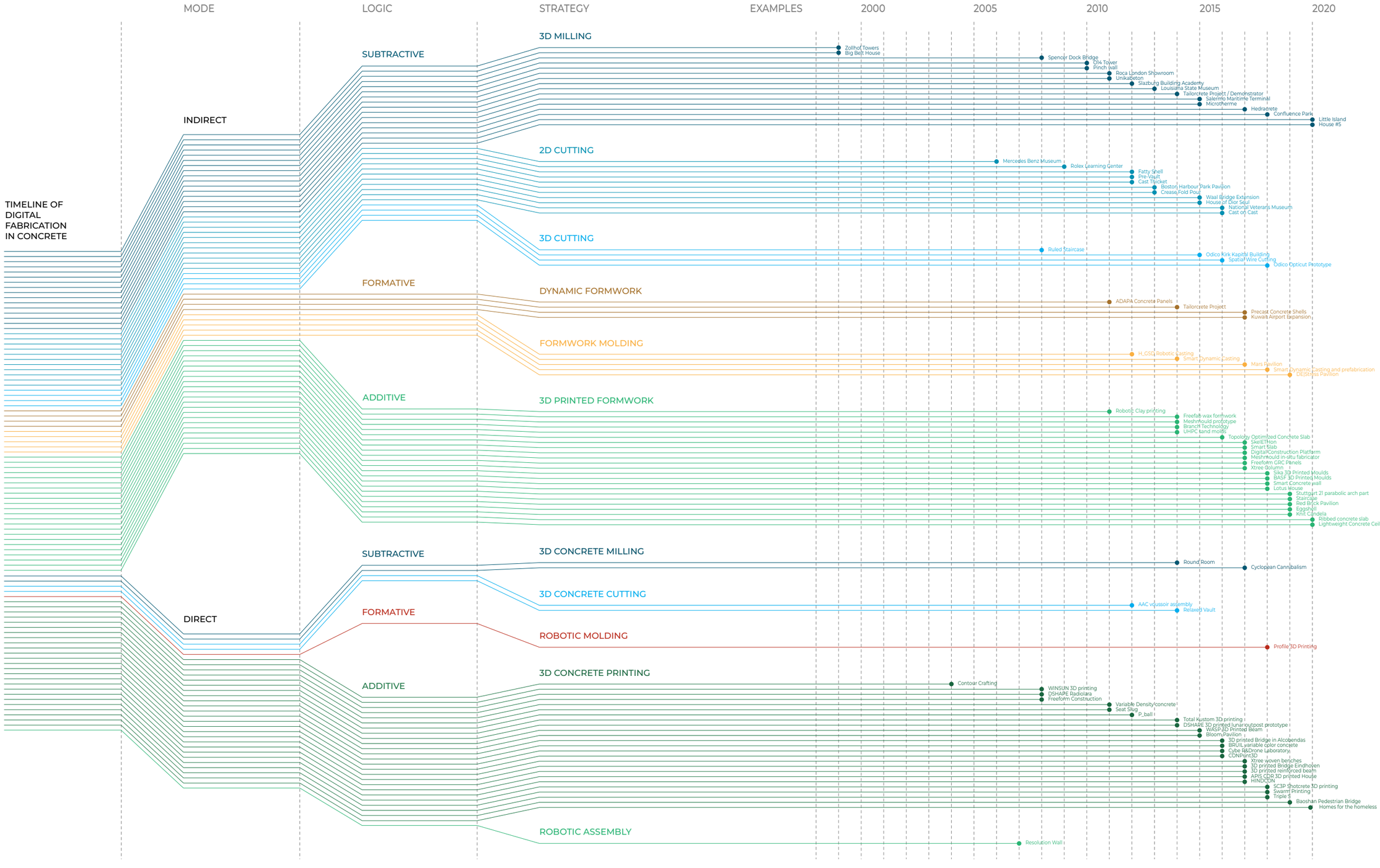


Figure 3.1: Digital fabrication strategies for concrete architecture. Categorization according to (1)Intervention Mode, (2)Transformation Logic, (3)Digital Fabrication Strategy and (4)Application types.

Figure 3.2: (interior) Digital Fabrication in Concrete: timeline of examples of different digital fabrication strategies.


MODE
LOGIC
STRATEGY
EXAMPLES
2000
2005
2010
2015
2020
TIMELINE OF DIGITAL FABRICATION IN CONCRETE
INDIRECT
SUBTRACTIVE
3D MILLING
Zollhof Towers
Big Belt House
Spencer Dock Bridge
DI4 Tower
Pinch Wall
Roca London Showroom
Unikalbeton
Salzburg Building Academy
Louisiana State Museum
Tailorcrete Project / Demonstrator
Salerno Maritime Terminal
Microtherme
Hedradrete
Confluence Park
Little Island
House #5
2D CUTTING
Mercedes Benz Museum
Rolex Learning Center
Fatty Shell
Pre-Vault
Cast Thicket
Boston Harbour Park Pavilion
Crease Fold Pour
Waal Bridge Extension
House of Dior Seul
National Veterans Museum
Cast on Cast
3D CUTTING
Ruled Staircase
Odico Kirk Kapitel Building
Spatial Wire Cutting
Odico Opticut Prototype
FORMATIVE
DYNAMIC FORMWORK
ADAPA Concrete Panels
Tailorcrete Project
Precast Concrete Shells
Kuwait Airport Expansion
FORMWORK MOLDING
H_GSG Robotic Casting
Smart Dynamic Casting
Mars Pavilion
Smart Dynamic Casting and prefabrication
DEJStress Pavilion
ADDITIVE
3D PRINTED FORMWORK
Robotic Clay printing
Freefab wax formwork
MeshMould prototype
Branch Technology
UHPC sand molds
Topology Optimized Concrete Slab
SkelETHon
Smart Slab
DigitalConstruction Platform
MeshMould in-situ fabricator
Freeform GRC Panels
Xtree Column
Sika 3D Printed Moulds
BASF 3D Printed Moulds
Smart Concrete wall
Lotus House
Stuttgart 21 parabolic arch part
Staircase
Red Brick Pavilion
Eggshell
Knit Candela
Ribbed concrete slab
Lightweight Concrete Ceiling
DIRECT
SUBTRACTIVE
3D CONCRETE MILLING
Round Room
Cyclopean Cannibalism
3D CONCRETE CUTTING
AAC voussoir assembly
Relaxed Vault
FORMATIVE
ROBOTIC MOLDING
Profile 3D Printing
ADDITIVE
3D CONCRETE PRINTING
Contour Crafting
WINSUN 3D printing
DSHAPE Radiolara
Freeform Construction
Variable Density concrete
Seat Slug
P_ball I
Total Kustom 3D printing
DSHAPE 3D printed lunar outpost prototype
WASP 3D Printed Beam
Bloom Pavilion
3D printed Bridge in Alcobendas
BRUIL variable color concrete
Cybe R&Drone Laboratory
CONPrint3D
Xtree woven benches
3D printed Bridge Eindhoven
3D printed reinforced beam
APIS COR 3D printed House
HINDCON
SC3P Shotcrete 3D printing
Swarm Printing
Triple 3
Baoshan Pedestrian Bridge
Homes for the homeless
ROBOTIC ASSEMBLY
Resolution Wall I

3.1.1 Indirect Processes: digital formwork fabrication

3.1.1.1 Indirect Subtractive Strategies: milling, cutting and slicing formwork

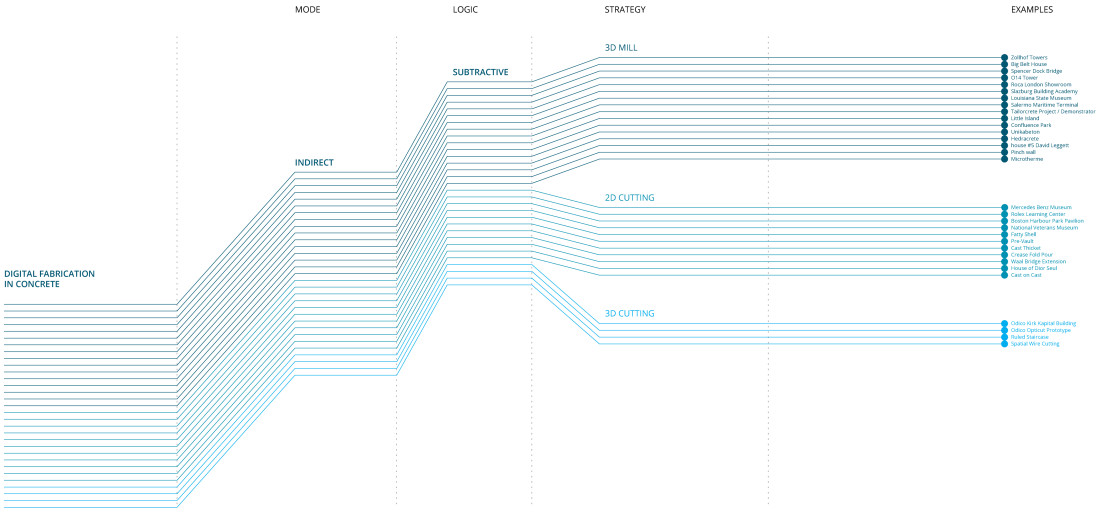


Figure 3.3: Indirect Subtractive strategies for digital fabrication in concrete.

Indirect Subtractive strategies (Figure 3.3) are based on the production of formwork through the use of a stock material (a three dimensional block, flat panel or membrane of various materials) and a digitally controlled tool that shapes the mould by removing or cutting excess material. Three main processes exist that will be detailed further:

1. 3D milling of stock material blocks
2. 2D cutting of flat panels and textile membranes
3. 3D cutting or robotic wire cutting of foam blocks

3D Milling

The use of digital fabrication technologies in architecture had some of its first developments in the mid-90s, precisely as an indirect solution to the problem of materializing complex geometries in concrete, through the production of non-standard formwork elements. As was described in the previous section, this was a large limitation of traditional concrete construc-



Figure 3.4: 3D milling processes: a) gantry type setup with 5-axis (Zollhoff Towers); b) Robotic 3D milling (Unikabeton).

tion processes and for this purpose, one of the earliest adopted strategies employed, was the use of computer-controlled subtractive manufacturing processes, particularly CNC milling.

Generally speaking, milling is a process characterised by the removal of material from an initial block, in successive passes, until the necessary final geometry is obtained. A parallel can be established with the manual process of a sculptor, where from a block of this material, through the controlled action of a tool, the excess material is successively removed until a desired shape is achieved. The digital version of this process presupposes the definition of geometry through a three dimensional model, from which a set of milling instructions is generated and later transmitted to a computer-controlled tool. This tool has the possibility of moving in space in the 3 Cartesian coordinates, describing tool paths, iteratively carving the stock material into the desired geometry. Depending on the number of available axis of motion (and the specific systems such as gantry structures or industrial robots) this digital fabrication strategy can be employed to create 3D curved surfaces with a high degree of complexity and detail, in the process we name 3D Milling (Figure 3.4).

In the case of concrete architecture, as mentioned earlier, this strategy can be used for the production of customised formwork elements with variable geometry for in-situ constructions or moulds for precast elements. The geometry of such formwork or mould elements is easy to extract from digital models and its negative counterpart can be used to design the necessary surfaces to be milled. One of the most used stock materials for this purpose is expanded polystyrene (EPS) blocks. For large built surfaces, similarly to other traditional formwork systems (e.g.,

wood shuttering or metal panels), the use of 3D milling for formwork production entails the subdivision of the surface or volume to be built, according to the dimensions available for the stock material. From this subdivision, a milling strategy is then defined for each of the formwork elements, which are subsequently produced one by one. In the case of in-situ monolithic constructions, the fabricated elements are applied on site, in conjunction with traditional falsework support systems[1], defining a continuous surface to be reinforced and cast. In the case of prefabricated elements, the digitally fabricated moulds are used individually or in larger assemblies to produce individual precast components with or without previous reinforcement strategies.

The finishing quality of EPS formwork elements manufactured through this process, and therefore of the cast concrete surfaces, depends on several factors, directly resulting from this manufacturing technology. Most notably, the diameter and shape of the milling tools and its speed of rotation and movement, in conjunction with the distance between tool passes. These parameters determine the resolution of the finished formwork surface which can be rough or smooth. This layer by layer and pass by pass process also results in a direct relation between the quality of the manufactured surfaces and the production time for its execution. As such, the higher the desired quality, the longer the manufacturing time needed. Thus, considering, the need to obtain high resolution surfaces for good concrete finishes results in considerably high manufacturing times usually in the magnitude of several hours per square meter (Feringa and Søndergaard, 2014). Moreover, other factors also influence the quality of the milled surfaces. Most notably, as a porous material with a cellular nature, when used directly, EPS leaves a clear impression of its texture on concrete surfaces necessaitating further treatments to achieve smooth surfaces.

Another relevant factor in this process is the generation of large amounts of material waste. This issue arises in two specific areas. In its current application, this process presupposes that for each mould created there is a block of material with an excess volume which is carved until the desired surface is obtained. As such, all the excess material resulting from this operation becomes waste in the form of a fine powder, which is difficult to recycle within this construction chain, although its recycling is possible for other uses. Secondly, and for the same reason, the destruction of the unwanted section of the stock material, implies a difficult material optimisation of the full volume of stock materials without resorting to other manufacturing processes (e.g., pre slicing EPS blocks). These factors, combined with the high fabrication times result in high production costs for 3D milled EPS formwork.

3D milling of formwork for prefabricated and monolitihc concrete constructions

[1] For instance, the integrated solutions by established companies such as PERI.

One of the first examples of the use of this technology in a large-scale concrete construction in the work of Frank Gehry, Neuer Zollhof, in Dusseldorf, in 1999.[2] The design is composed of 3 different buildings, with a variable curved geometry, materialized with different construction systems. In the case of tower B, the apparently continuous curved façades were in fact divided, floor by floor, in a set of self-supporting concrete wall panels, each containing a section of the wall and a window, to be precast using individual 3D milled EPS moulds.

Fabrication information and geometry for each of the 355 elements was extracted directly from a main digital model, produced in the CATIA software (Computer Aided Three Dimensional Interactive Application) by the design team and the respective negative mould geometry was designed. This information was then used to program a 5-axis machining system that milled the individual moulds from large EPS blocks (Figure 3.5a)). Afterwards, the moulds were reinforced with a steel mesh, cast and hand-finished on their outer face. This milling process left visible textural marks on the surface of the EPS moulds that were transmitted to the interior contact surface of the precast elements when cured. These marks resulted from the shape and dimensions of the tool and the distance between tool paths which was purposely large in order to decrease fabrication times. After assembly on-site, the wall sections were finished with an external layer of steel panels and an interior layer of drywall, rendering the actual concrete invisible, a fact that made this trade-off between production time and economic feasibility and finishing quality as a possible solution.

Considering this issue, Dennis Shelden, chief technology officer of Gehry Technologies, refers in "Digital surface representation and the constructability of Gehry's architecture" (Shelden, 2003):

> "The feasibility of this process resulted directly from efficiencies found in the CNC mould forming process. The low strength of Styrofoam allowed it to be routed at extremely high speed, reducing the machine time cost. Relatively low tolerances and allowable roughness of the mould finish allowed the routing to be done with a single pass of a large (approximately 2") bit."

Another early relevant example in this category, for large-scale monolithic concrete constructions can be found in the Spencer Dock Bridge by Amanda Levete / Future Systems Architects, built in 2009, in Dublin, Ireland (Figure 3.5 b)). The design of the bridge, with 40 meters in

[2] It was also one of the first relevant works where the use of both CAD and CAM technologies was central in both the design and construction stages in an integrated process based on a central digital architectural model described by Gehry as the "master model" (Shelden 2002, 51)



Figure 3.5: Two examples of 3D milling of EPS formwork for precast and in-situ concrete architecture and respective formwork elements: a) the Zolhof Towers by Frank Gehry, 1999, where the exterior non-bearing walls were composed of precast concrete panels; b) the Spencer Dock Bridge by Amanda Levete Architects, 2008; c) the Zolhof Towers 3D milled EPS formwork blocks before reinforcement and casting; d) the Spencer Dock Bridge formwork elements for one of the center pillars assembled in scaffolding on-site, before reinforcement and casting.

length by 25 meters in width, is composed of a fluid set of surfaces of single and double curvature, defining on its lower face a continuous transition between the deck and the two vertical supports. The solution used to materialize this work was based on the potential of the CNC milling process to recreate this type of geometries using EPS moulds. For this purpose, the continuous under surface of the deck and supports was subdivided into a regular grid of approximately 3 meters by 1.25 meters, defining a set of formwork blocks with similar dimensions and variable heights depending on the local curvature of the surface, to be milled in EPS (Figure 3.5 d)).

Contrary to the previous example, the bridge surface was intended to be finished in exposed concrete, posing the added difficulty in the need for a high quality smooth finish on formwork parts. To achieve this, the moulds were produced by the Dutch company NedCam, in high density EPS, with a 5-axis CNC milling system. At this stage, to counteract the porosity of the EPS surface and ensure the desired finish in the concrete, the moulds were manually sprayed with a waterproofing agent and polished. The blocks resulting from this process were then transported to the construction site and assembled on wooden falsework tables with previously defined fittings, with its positioning being controlled by a georeferencing system based on the geometry of the digital model. Because the regular geometry of the formwork subdivision was defined taking into account its ease of execution and transport and not as part of the design language, its direct translation into the finished surfaces was not a desired outcome. To mitigate this, a network of linear elements was created on the EPS surface, defining "dummy" rebates on the final concrete surfaces, with a design derived from directly derived from the fluid geometry of the bridge (Dempsey, 2008).

The Spencer Dock Bridge case expresses the applicability of this process for the precise definition of continuous surfaces with a high variety and degrees of curvature, both for in-situ constructions and for prefabricated elements. Likewise, and taking into account the need for several steps in the preparation of the formwork (from successive milling works per piece, to manual coating and polishing) it exemplifies the still remaining difficulties in generating surfaces with high finishing qualities without additions in manufacturing time and labor.

Several other works illustrate current applications of this technology, for in-situ or prefabricated applications. Cases such as the support structure and ribbed and textured roof of the Salzburg Building Academy by Soma Architects, 2012; the prefabricated interior cladding panels for the Louisiana Sports Hall by Trahan Architects, 2013; the continuous curved roof of the Salerno Cruise Terminal by Zaha Hadid Architects (2015) or the roof structure in Confluence Park by Matsys (2018) (Figure 3.6) used variations of this manufacturing technology to materialize dif-

ferent types of structures in exposed concrete, demonstrating its applicability and widespread use in the panorama of contemporary architecture, notwithstanding its recognized issues of material and production costs.

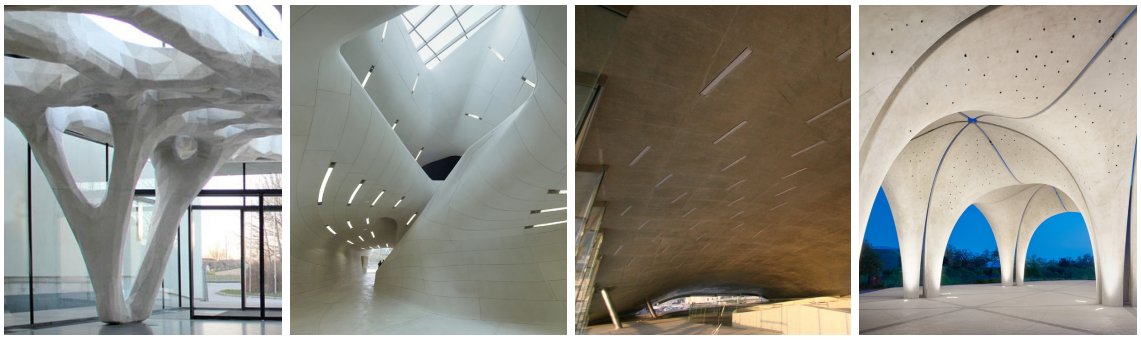


Figure 3.6: Examples of 3D milling for concrete formwork in current practice, showcasing their use for precast and in-situ applications: a) Extension of the Salzburg Building Academy, Soma Architects, 2012; b) Louisiana Sports Hall of Fame, Trahan Architects 2013; c) Salerno Cruise Terminal, Haha Hadid Architects, 2015; d) Confluence Park, Matsys 2018.

In the academic field, several research projects developed in recent years have sought to optimize 3D milling processes for EPS moulds for the construction of non-standard concrete structures, with particular focus on robotic manufacturing technologies. Prototypes such as Unikabeton (2011) (Dombernowsky and Søndergaard, 2011) and the Tailorcrete Demonstrator (2014) (Figure 3.7), explored in multiple built prototypes, several issues around this process, namely the optimization of the design process and manufacturing strategies seeking to reduce costs and manufacturing times; exploring its applicability in particularly complex geometries other than smooth curved surfaces; study of formwork materials other than EPS and strategies for the execution of high quality finishing surfaces(Feringa and Sondergaard, 2012), (Thomas Juul Andersen, 2016).

The suitability of 3D milling for creating precast concrete elements with complex geometry has also been explored in this dissertation through practical experimentation and is presented in section 4.2 - 3D milling vs RHWC

2D Cutting

As mentioned in the first chapter of this dissertation, a large part of concrete architecture, until the emergence of digital design and manufacturing tools in the mid nineties was based on the construction of complex forms, frequently characterized by the need of optimizing and ratio-



Figure 3.7: Academic prototypes featuring research into 3D milling for EPS concrete formwork: a) The Unikabeton Prototype, developed to test the feasibility of particularly complex geometries; b) the Tailorcrete Project final prototype.

nalizing formwork construction processes. Cases already mentioned such as the ruled geometry of Felix Candela's works, the use of spherical surfaces in the Sydney Opera House or even the symmetry in most of Heinz Isler's works demonstrate the relationship between the buildability of the formwork required for concrete construction and the final design geometry.

One of the most common types of formwork used in these cases was wood formwork. In these cases, the curved geometries were rationalized and approximated by the successive addition of flat identical elements, such as planks or panels through manual work. Besides the increase of labor related construction costs and times, this can result in limitations in the geometric complexity of designs, reduced precision and in undesired formal and textural aspects such as rough formwork textures in visible concrete surfaces and surface edges from planar formwork elements when trying to describe curved surfaces.

The introduction of digital design and manufacturing technologies has allowed for an expansion in traditional wood formwork systems based on the possibility of manufacturing parts with varied and complex geometries from planar materials. As such, in the scope of this thesis, 2D cut formwork pertains to digital fabrication processes for the production of concrete moulds which imply the description of a given concrete surface or 3D element, using CNC cutting processes such as 2D milling or laser cutting to shape planar materials for assembly as formwork.

One of the main applications of this type of strategy is on the construction of freeform, monolithic concrete structures. It has been used in several iconic projects such as the Mercedes Benz Museum by UN Studio (2006), the Rolex Learning Center (2008) and the more recent Extended Waal Bridge by Zwarts Jansma Architects (2016) (Figure 3.8).

In the case of the Rolex Learning Center, the design proposed a free plan of 121.5mx162.5m,

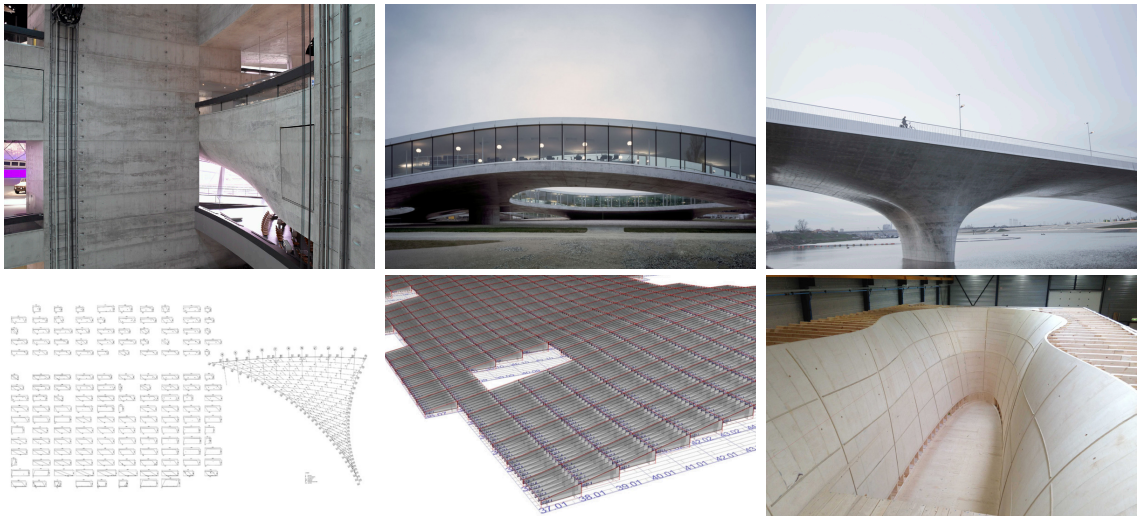


Figure 3.8: Built works using of 2D cutting of formwork and respective formwork elements: a) BMW Museum by UN Studio, 2006; b) Rolex Learning Center by SANAA, 2009; c) Extended Waal Bridge by Zwarts Jansma Architects, 2016.

in which the different spaces of the program were separated by undulations of a continuous concrete slab. This aspect, central to the work, posed considerable difficulties in its execution, considering the need to create a continuous double curved surface with an exposed concrete underside, for which traditional wood formwork solutions would not be adequate.

As is described by Weiland at al. (WEILANDT et al., 2009), fabrication of the formwork involved the subdivision of the concrete surface in a 2.5 meters square grid for which 1455 customized formwork platforms were built. Each individual platform was composed of a set of vertical ribs with a horizontal lower edge and a curved upper edge, following the designed surface. The actual formwork surface was composed of a layer of boards and a final smooth laminated chipboard and all of the formwork construction geometry and CNC data was derived from a central 3D model and used in CNC cutting more than 10 000 individual ribs. Similarly to the case of the Spencer Dock Bridge, mentioned in the previous section, the formwork platforms were assembled on-site with standard scaffolding components for alignment in the z axis (Scheurer, 2010).

The precision of the digitally fabricated wood formwork resulted in the case of the Rolex Learning Center, in a smooth curving concrete surface, directly translating the design geometry without any rationalization arising from fabrication constraints.

When compared to 3D milling of moulds in EPS, the field of possible geometries described by this process is naturally smaller. Namely, although it is possible to describe double-curved

surfaces, the radii of local curvature of these surfaces are generally larger, dictated by the characteristics of the formwork material and the need for outer surfaces to be bent under pressure to assume their final shapes.

As was apparent in the Rolex Learning Center example, one other crucial aspect of this formwork production strategy lies on the quality of visible surfaces, difficult to achieve using other processes. The resulting concrete surfaces generally have a higher quality of finish, due to the use of materials of a planar nature with smooth, non-porous textures (eg melamine, plywood, chipboard, etc).

2D cutting of formwork for precast components & assemblies

In addition to the of large scale monolithic and continuous concrete surfaces, for which this family of processes are particularly suitable, 2D cutting is also a relevant process in the construction of precast concrete structures, particularly those composed of small scale variable discrete components. One interesting formwork design strategy that takes advantage of 2D cutting is folding. Moulds, fabricated by planarizing a 3D geometry, cutting the resulting patterns from a sheet material and folding them into shape to be used for casting concrete components. This "unroll – cut – assemble" formwork fabrication strategy can be found in several research prototypes, such as the Pre:Vault Pavilion, the Cast Thicket (2014) (Tracy et al., 2014) and Crease, Fold Pour (2013) (Kaczynski, 2013), as it is a low cost, low material, low labor, quick process to achieve differentiated designs.

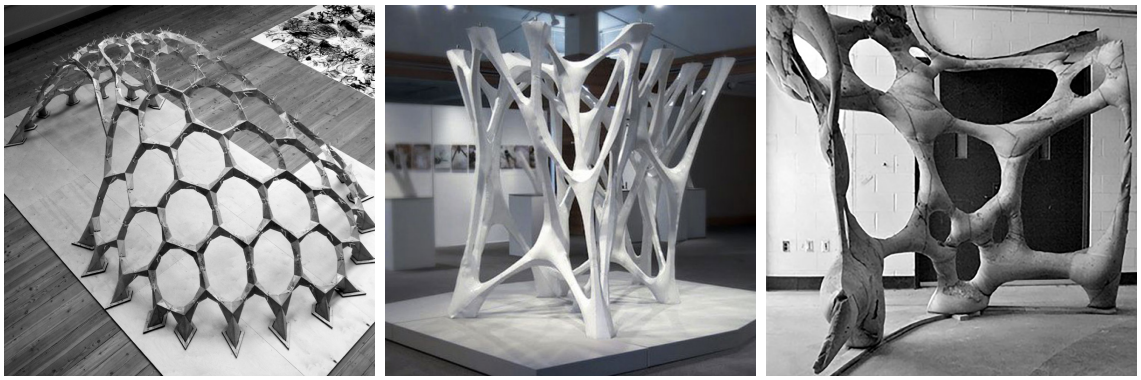


Figure 3.9: Examples of academic prototypes using 2D cut formwork: a) Pre:vault Pavilion, 2011; b) Cast Thicket, 2014 and c) The Fatty Shell, 2012.

The Pre:Vault Pavilion (Figure 3.9 a)), built for the the 2011 Aarhus Cultural Night at the Aarhus school of Architecture points to this interesting subset of architectural concrete experiments, that focuses on lightweight prefabrication. The pavilion featured a funicular freeform vault,

composed of 112 unique Y shaped components resulting from an algorithmic form finding process. The design of these components, with flat surfaces, enabled the planarization of their geometry and fabrication, using CNC laser cutting and PETG plastics. Each formwork component was then folded back into its volumetric form, reinforced and cast and all components were subsequently assembled, using a scaffolding structure also built using 2D cutting procedures (Larsen et al., 2012).

These are clear examples of the potential of integrating digital fabrication into the concrete casting process and taking it into consideration in the general design stage, to achieve innovative architectural solutions.

Other 2D cutting solutions - Flexible formwork

Although most formwork solutions that use 2D milling or cutting use rigid materials, such as the ones presented above, some solutions have been explored in deformable materials, such as textiles, using similar 2D cutting processes.

Non-rigid and non-static formwork systems have been less used in the history of concrete production; However, they are also starting to integrate digital fabrication technologies in their specific processes. Of particular relevance is the use of fabric formwork. Such solutions take advantage on the ability of fabrics to deform under the weight of the poured concrete to achieve smooth curved geometries without the need to previously define them with rigid materials. Although various researchers are currently exploring the potential of flexible textile formwork, some built prototypes and literature tend towards the use of craft-based approaches for building components such as columns, beams, walls and thin shells (Veenendaal et al., 2011). Such craft-based approaches usually focus on the tectonic, formal and textural effects directly resulting from these formwork solutions, in line with past experiments, already mentioned in Concrete and Architecture (chapter 2), such as the works of Miguel Fisac and Bruno Musmeci.

Nevertheless, recent developments also exist, that explore this formwork material in conjunction with digital design and fabrication processes. This enables the expansion of previously available processes by increasing possible complexity and precision of the fabric cutting patterns thus enabling very expressive freeform concrete structures with minimal formwork material usage, within the particular language of fabric cast concrete. On such example is the Fatty Shell prototype (2012) (Sturgeon et al., 2012) (Figure 3.9 c)). While fabric formwork solutions of the past relied on simple, often symmetric shapes, the use of generative design and physical simulation softwares such as grasshopper, allows designers to achieve complex designs with a high degree of variability which can be tailored to be built using fabric formwork. Using 2D cutting

processes, these types of structures can be digitally flattened or unrolled, producing a set of 2D patterns for cutting. The CNC cut fabric parts can then be assembled and stitched into a final form that is usually suspended, tensioned and cast assuming the designed shape with the weight of the poured concrete.

3D Cutting

As previously state, 3D milling strategy focuses on the three-dimensional carving of stock materials to create complex formwork solutions for concrete. 2D cutting uses similar fabrication tools, but operates in a limited 2D space. As a middle ground, 3D cutting, takes advantage of the speed of cutting processes vs milling processes, and adds a third degree of freedom, allowing for spatial cutting operations. This fabrication strategy is possible, using the combination of 3 elements: a) a linear cutting tool, such as a wire (abrasive or hot), b) a robotic arm, responsible for its movement in 3d space and c) an easily cut stock material. One of the most relevant technologies using this strategy is Robotic Hot Wire Cutting (RHWC) of EPS moulds.

Robotic Hot Wire Cutting is a recent technological evolution of traditional cutting processes already found in industrial and pre-industrial settings. Traditional wire-saw cutting is a process by which a tensioned fiber or metallic wire is used as an abrasive tool to carve or cut large volumes of materials such as clay (pre-historic wire saws), wood (scroll-saws) and stone (diamond-wire saws) (Jones and Simons, 1961), (Smogorzewska, 2007). Hotwire cutting is a development of such processes, substituting the abrasive action with heat. This is generally achieved through the use of an electric charge passed through the wire acting as a resistance and heating to a temperature of approximately 200º C, thus allowing for the easy cutting of materials with a low melting point. 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. Later industrial developments have paired this process with different automation mechanisms such as 4 axis CNC gantries (Figure 3.10).

Thus, Robotic Hot Wire Cutting is a digital fabrication technology that employs this 3D cutting strategy, enhanced and adapted to the construction industry, by employing a hot wire end-effector attached to a multi-axis robotic arm, drastically increasing the freedom and scale of previous wire cutting tools. This setup can thus be used as a digital fabrication tool to cut complex-shaped components in foam-like stock materials (Figure 3.11). By moving the heated wire in a digitally controlled path through space, a solid block of stock material can be precisely sliced. By extracting these paths from a digital 3D model and sequentially chaining the slicing

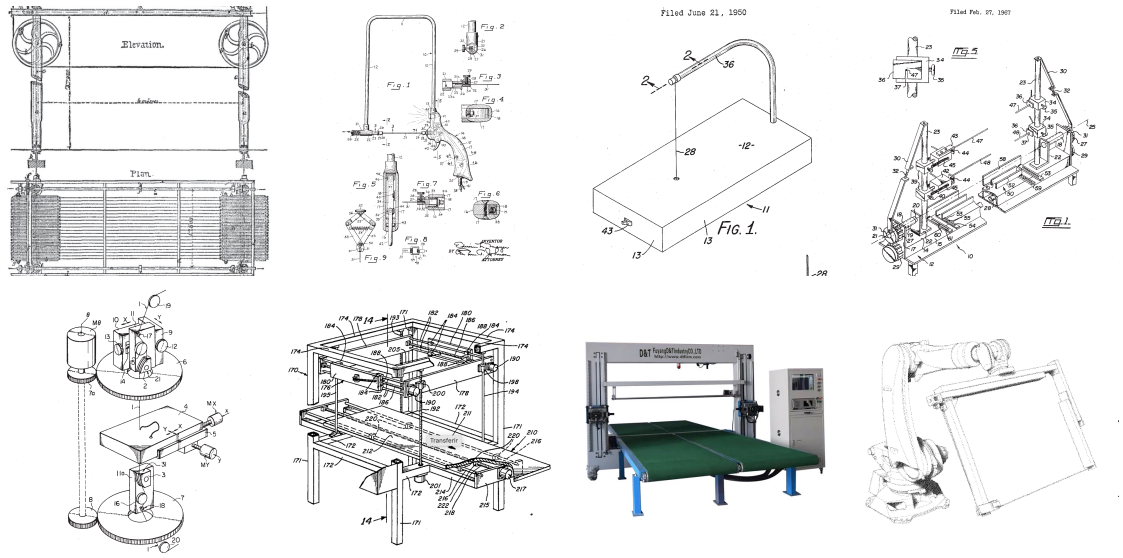


Figure 3.10: Evolution of wire cutting processes. From upper left: a) wire stone saw, 1885; b) electrical scroll saw (1934); c) unit for cutting materials by heat (1950) d) hot wire cutting machine (1967); e) numerically controlled wire-cutting electrical discharge machine; f) foam cutting apparatus (1987); g) CNC 3D hot wire foam cutter, 2021 ; h) robotic hot wire cutting system (2021).

operations, a complex 3D volume can be carved. In the case of concrete architecture, RHWC can be used to produce mould parts for in-situ or precast components, with applications similar to those referred in the first section of this chapter.

One of the main features, setting RHWC apart from other digital fabrication solutions is its geometrical limitations. On one hand, the use of multi-axis robotic arms allows for a large degree of geometrical freedom and work envelope dimensions. On the other hand, considering that any movement of the cutting wire represents a line travelling through 3D space, ultimately only ruled surfaces can be described and as such, only these types of geometries can be realized using RHWC. Nevertheless, if needed, more general double curved surfaces can be approximated through geometry rationalization processes such as ruled strips (Flöry and Pottmann, 2010).

Another important feature of RHWC is its operating speed. When compared with the subtractive processes mentioned earlier in this section, CNC Milling and 2D cutting, RWHC is a considerably faster process. This is a consequence of the material properties of EPS and the dimensions of the cutting surface of the wire. The low density and low melting point of EPS allows for the material to vaporize in front of the length of the cutting wire, resulting in minimal material resistance and fast cutting speeds for large surfaces.

In the research field of architecture, RHWC was introduced in the early 2010s, with early exam-

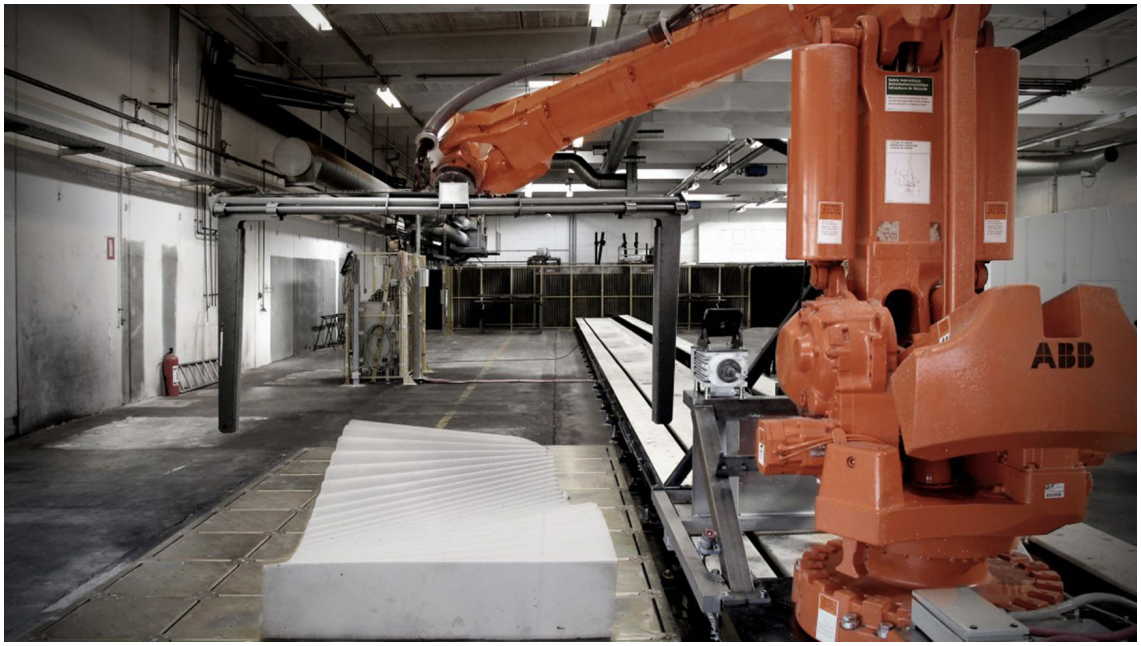


Figure 3.11: Example of a Robotic Hot Wire Cutting setup at Odico Formwork, cutting a solid EPS block.

ples in the previous decade using similar processes with 4-axis gantry systems, specifically tested for concrete formwork production or mentioned as such in literature (Kieferle et al., 2008), (Rippmann and Block, 2011).

Although acknowledging the possibility of using RHWC for the fabrication of formwork for concrete, most of the first experimental architectural prototypes focused on exploring the design possibilities of prefabricated light structures directly assembled in EPS blocks with variable geometries. Works such as the Automated Foam Dome by Thibault Schwartz (2012) (Schwartz, 2012) and the Periscope Tower by Matter Design Studio (2010) (McGee et al., 2013) were early examples of the possibility of creating complex curved structures within the geometrical limitations of RHWC technology (Figure 3.12 a,b) .

Another later example of the exploration of RHWC is the RDM Vault (2012), a prototype structure built through the collaboration of Matthias Rippmann, Silvan Oesterle and Jelle Feringa. The project focused on the design and construction of a funicular vault structure, using RHWC for the production of the individual voussoirs. The vault was composed of 53 individual components, all cut from the same EPS stock block with variable curved geometries and assembled in a structure of approximately 8 by 10 by 3.5 meters. Although no casting was used, and thus the true potential of RHWC, fabrication parameters and limitations for concrete formwork wasn't tested, the design of the RDM vault established evident parallels between the traditional pro-

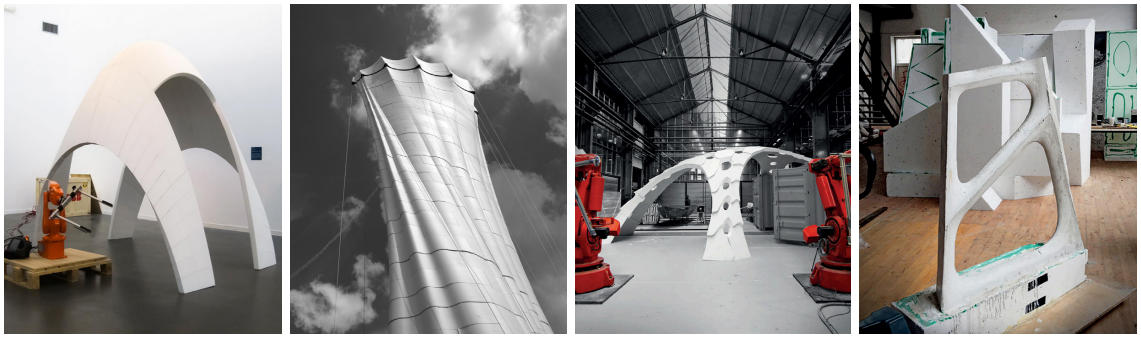


Figure 3.12: Examples of foam prototypes and precast elements using Robotic Hot Wire Cutting (RHWC): a) Automated Foam Dome by Thibault Schwartz, 2012; b) Periscope Tower by Matter Design Studio, 2010; c) RDM Vault by Matthias Rippmann, Silvan Oesterle and Jelle Feringa, 2012; d) Opticut Prototype by Asbjørn Søndergaard and ODICO, 2014.

cesses of stone cutting and Robotic Hot Wire Cutting. By defining the voussoir shapes as the result of slicing operations and accentuating the variability of the perimeter geometries of the components, it used the geometrical constraints of RHWC process as design parameters establishing a feedback relation between construction technology and design particular of RHWC (Figure 3.12 c).

A more recent project, the Opticut prototype (2014-2018) (Figure 3.12 d) directly explored the possibility of using RHWC for formwork production of prefabricated concrete elements. In this case, the prototype design focused on the use of topological optimization (TO) processes in combination with a RHWC fabrication strategy. Here, Robotic Hot Wire Cutting was used to produce moulds for the complex shapes resulting from TO which would be prohibitively material and time-consuming using CNC milling. Initial prototypes used RHWC for the mould fabrication, by cutting voids in EPS blocks and using them as inserts in conventional shuttering systems. Although the process involved geometry rationalization to approximate the non-ruled surfaces resulting from TO resulting, it demonstrated the feasibility of such geometries using RHWC and EPS moulds. Moreover, it demonstrated the possibility of material savings both in the amount of concrete used (the purpose of T.O) and more relevantly, in the amount of formwork materials wasted and fabrication times resulting from the RHWC process(Feringa and Søndergaard, 2014).

More recent developments have attempted to overcome the geometric limitations of ruled surfaces through the exploration of flexible blades and multiple robot setups, allowing for the direct creation of more general double-curved surfaces without the need for approximations to ruled surfaces (Søndergaard et al., 2016), (Rust et al., 2016).

3.1.1.2 Indirect Formative Strategies: dynamic and moulded formwork

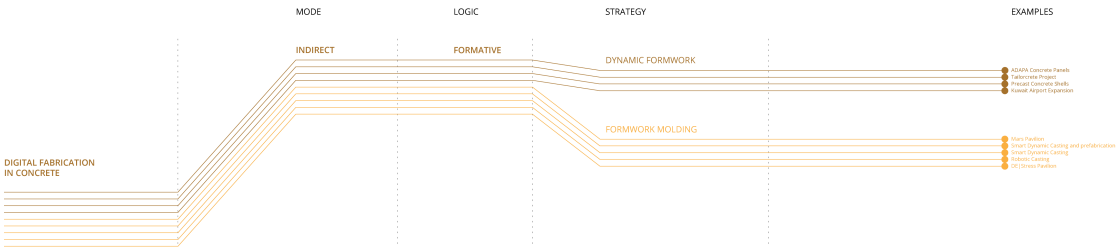


Figure 3.13: Indirect Formative strategies for digital fabrication in concrete.

An alternative approach to subtractive processes in mould production is to use formative processes. In the case of concrete fabrication, this logic translates into 2 categories of formwork.

1. Dynamic formwork systems that are reconfigurable to assume curved geometries prior to concrete casting.
2. Formwork moulding systems that feature robotic fabrication to directly and precisely deform a formwork material for casting.

Dynamic Formwork

Generally, dynamic formwork systems consist in such strategies that use the reconfiguration of a mould or its displacement in space to produce variable concrete shapes. Approaches that fall in this category join some of the benefits of rigid formwork (e.g. the reduced difficulty of achieving smooth surfaces) with a higher degree of formal freedom through adaptability or spatial movement. One large category of such cases is the use of adaptive moulding tables that can assume arbitrary curved shapes through the use of a pin system and a deformable membrane surface (Figure 3.14).

Adaptive or reconfigurable moulds have been used since the mid 19th century in several industries, from transports, to energy, to aerospace (Munro and Walczyk, 2007), with the first recorded patent of an adaptive moulding system for the production of concrete architectural elements dating to 1979, by Eisel (Hawkins et al., 2016). Schipper (Schipper, 2015) describes the evolution of these mould systems from early patents, well into this decade with little variation from the initial idea of a reconfigurable pin-matrix and an important point of departure with the introduction of digitally controlled CAD/CAM pin systems.



Figure 3.14: Adaptive formwork table by ADAPA - Adaptive Moulds (D-200), using a computer controlled pin system (without surface membrane).

Scaling these pin matrixes to the necessary dimensions for concrete casting, allows for the definition of a general curved surface, through the use of a deformable membrane on top of the pin system. This deformed surface is usable as a one-sided mould, for panel-like concrete elements, either directly on the moulding surface or by creating an intermediate mould from materials such as compacted sand or wax. Designwise these methods allow for the description of arbitrarily double curved surfaces, within the geometric boundaries of the moulding table. When coupled with robotic or CNC actuators, such systems can be fed with digital information from 3D models of the intended surfaces which is translated into the necessary coordinates for the pin system.

Several different applications of this method have been developed to date, with varying matrix densities, ranging from a small number of guiding actuators (Pronk et al., 2009) to dense pin fields (Peters et al., 2017). Also, from the initial manual systems, different actuation processes have been developed, such as robotically actuated rods and more advanced self-actuated pin fields (Raun et al., 2011; Gramazio et al., 2012).

Examples include the commercially available adaptive mould system from the danish company, ADAPA, for the production of thin variable precast concrete panels in several built projects. Also the several academic prototypes for precast and in-situ solutions, built using digitally reconfigurable tables for wax moulds, in the Tailorcrete research project at ETHZ (Gramazio

et al., 2012) and the thin wall precast panel system, developed in 2017 at the Graz University of Technology, using a robotic actuated pin system producing compacted sand moulds (Peters et al., 2017)(Figure 3.15 a,b,c). An adapted version of this fabrication technology was also used in the construction of the roof panels for the Arnhem Central Station in 2015, by UN Studio. In this case, the system featured a table with 21 manually adjustable pins and was responsible for the production of more than 1400 individually curved GFRC panels (Hoppermann et al., 2015).

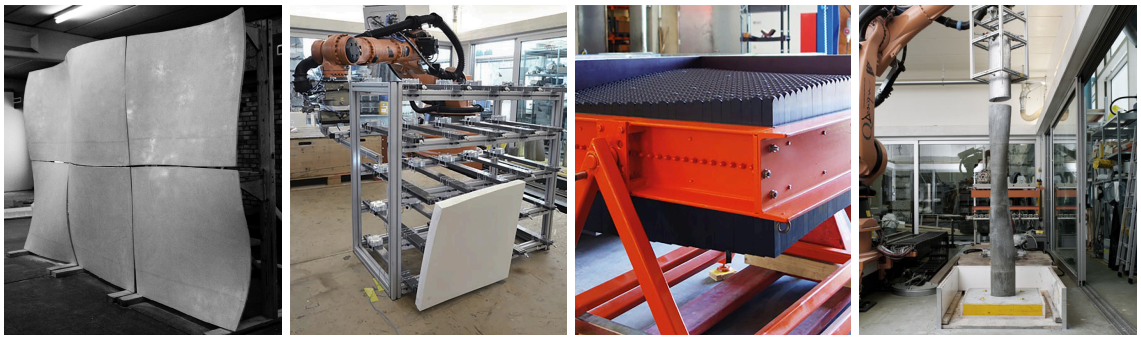


Figure 3.15: Examples of dynamic formwork strategies and applications; a) precast concrete panels using ADAPA dynamic formwork systems; b) early dynamic formwork prototype developed in the Tailorcrete project, using a robotic arm as actuator; c) dense pin matrix robotically actuated, developed at the Graz University of Technology; d) Smart Dynamic Casting system, using a robotic assisted dynamic mould.

Other dynamic formwork solutions - robotic molds

Aside from reconfigurable molding tables, other experiments have embraced the idea of a dynamic mould that can move in three-dimensional space during the casting process or the curing phase of the concrete mix, to produce structures of variable configurations. The Smart Dynamic Casting system, developed at the ETHZ (Lloret Kristensen et al., 2013) is based on this logic, applying robotic fabrication to the traditional dynamic formwork process of slipforming (Figure 3.15d).

While traditional slipforming uses a system of elevators to vertically move formwork sections, resulting in the construction of extrusion shapes only, the Smart Dynamic Casting system introduced the possibility of robotic movement and a variable mould section, greatly increasing the realm of possible geometries. A system of variable facade mullions was built with this process for the D-FAB house, in Zurich, in 2018, showcasing the effectiveness of this process to produce variations of precast column-like elements of varying sections, without the need of complete individual moulds (Lloret-Fritschi et al., 2019).

Generally speaking, all instances of the digital fabrication methods presented here benefit from

a high degree of adaptability and reusability, stemming from their dynamic and reconfigurable natures. The reusability of such systems, coupled with the use of environmentally friendly and reusable materials, such as sand or wax generally create concrete moulding systems with a particularly high level of sustainability.

While the production of general double curved surfaces is possible in adaptive moulding tables, the possible geometries described by the pin fields are limited to those similar to 3-axis milling, and further limited to large local curvatures that can't go below the available "pin resolution". One key difficulty with these processes is their limitation to the specific sizes of the moulding tables as well as the need of other strategies to define perimeter geometries different from the actual moulding table boundaries or regular rectangular shapes.

Considering it reusability, range of possible geometries and the high finishing surface qualities, resulting from the use of plastic membranes, these systems currently show a tendency towards the prefabrication of double curved and high-quality paneling systems with a high degree of surface geometry, but with conditioned perimeter shapes.

More customized dynamic solutions, such as the Smart Dynamic Casting system, are evidently more limited in applicable geometries. Nonetheless, they present an interesting tectonic potential in the strict connection of the fabrication process with its emerging design vocabulary.

Formwork moulding

Other formative processes can include the use of robotic systems for the production of moulds which are not dynamic or reconfigurable in themselves, but employ deformable materials for similar purposes. In the scope of this thesis, we name such processes, robotic formwork moulding, considering the direct actuation of a robotic system on a bendable or deformable moulding material that changes its shape to achieve a desired configuration for casting. Several such approaches have been developed with this principle, using different materials such as sand, clay, metal and fabrics.

At the ETHZ, Gramazio Kohler have developed several experimental prototypes, with robotic moulding for formwork production, using sand and clay, in the "Procedural Landscape" courses at ETH Zurich and the "Robotic Clay moulding" workshop, in IAAC, Barcelona , which were further developed in the TailorCrete project (Gramazio and Kohler, 2012), already mentioned in previous sections and, more recently, at the BALL state university, in the DE|stress pavilion (Miller and Battaglia, 2019) (Figure 3.16 a,b,c). In all of these cases, a bed of a selected mould-

able stock material is prepared with set dimensions within a working volume and deformed through the action of a 6-axis robotic arm with a sculpting end tool. The digitally controlled movement of the robotic tool can thus create variable shapes and interesting topologies on the surface of the deformed materials. The deformed and hardened surfaces can then be directly used as moulds for concrete casting or as intermediary moulds if the material is not suited for direct casting (i.e. clay).

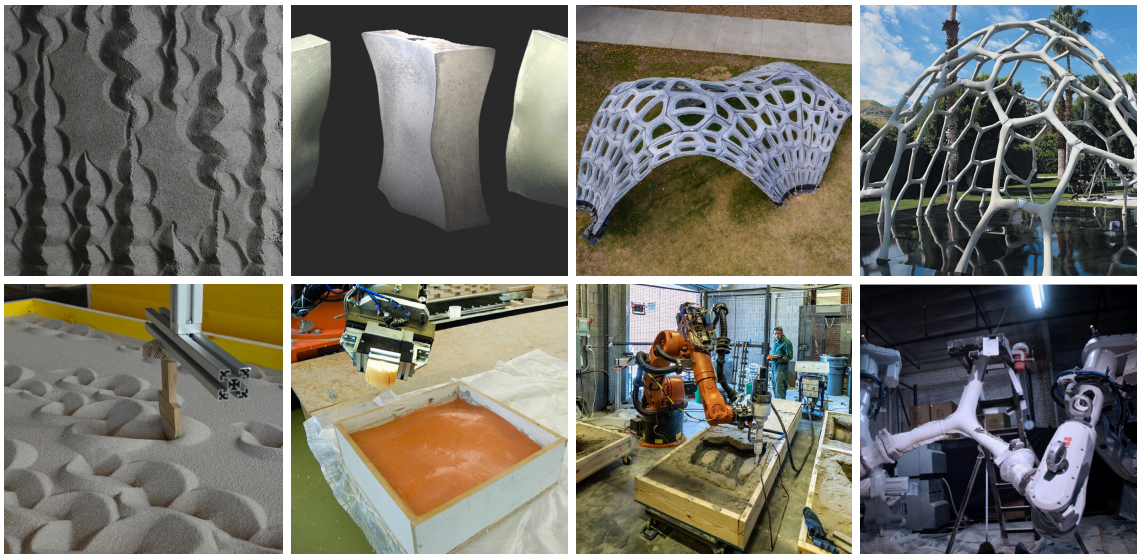


Figure 3.16: Concrete prototypes for precast components using a formwork moulding strategy: a) Precast panels resulting from robotically deformed sand moulds at the Procedural Landscapes 2, ETHZ elective course, Zurich 2011; b) robotically deformed clay moulds from the TailorCrete Project, ETHZ, 2012; c) DE|stress assembled pavilion and robotic carving of clay moulds; d) Mars Pavilion, full structure and robotic textile mould deformation of one component during casting.

Other experimental prototypes use the same logic of deforming a mould material into shape, but employ fabric materials, taking advantage of their ability to easily assume curved shapes and complex configurations without large expenditures of energy. This concept builds on previous explorations with the use of fabric formwork and digital fabrication, such as the already mentioned Fatty Shell Structure. The main difference in the case of robotic formwork moulding with fabric formwork is that instead of using digital fabrication tools merely for cutting 2D curved fabric patterns, digital robotic tools are used to directly shape the fabric in place before or during casting.

One interesting example can be found in the Mars Pavilion (2017), developed by Form Found Design, from previous experiments at UCLA by the authors (Culver et al., 2016) (Figure 3.16d). The design of this research pavilion employed seventy unique precast Y shaped components,

defining a parametric form-found lattice-like funicular vault. The fabrication process involved a first step of unrolling each components geometry and cutting the respective custom 2D nylon fabric pattern to be stitched shut. A second step, employed a robotic setup composed of two 6-axis robots working in tandem to stretch and move the Y sleeve ends into their predefined shape, using spatial information from the digital model. During this process, the Y sleeves were cast with a fast-setting concrete mix, reinforced with steel fibers and after curing, the components were assembled using metal connectors into the finished self-supporting structure (Sarafian et al., 2017).

In general terms, one of the main advantages of robotic formwork moulding is precisely in the use of formative instead of subtractive processes. Generally speaking, forming is a non-destructive process and requires less energy than subtracting. This results in an obvious reduction of energy costs, material consumptions and waste production when used in the fabrication of formwork for concrete, particularly when compared with CNC milling (Culver et al., 2016).

From the examples here presented, robotic formwork moulding in general has been demonstrated to be a possible solution for in-situ cast structures by way of producing formwork parts from materials that can be used for casting (i.e. wax) which are usable on-site, in conjunction with standard forming tables and accessories, similarly to the process described in the Spencer Dock Bridge project. Nevertheless, the cases presented earlier also point the use of robotic formwork moulding to the production of precast concrete façade panels and structural components.

The lexicon of possible forms within this fabrication logic depends greatly on the materials and end-effectors used, ranging from freeform surfaces similar to 3-axis milling, to customised carved surfaces when specialized end-effectors are used, to the formal language specific of fabric formed concrete when textile moulds are employed. In all cases, from the architectural point-of-view of this dissertation, the main point interest in robotic formwork moulding, more than material or procedural optimization, appears to be the close relation that can be established between design and construction, visible in the easily identifiable languages that relate material, tool, process and form.

3.1.1.3 Indirect Additive Strategies: printing formwork

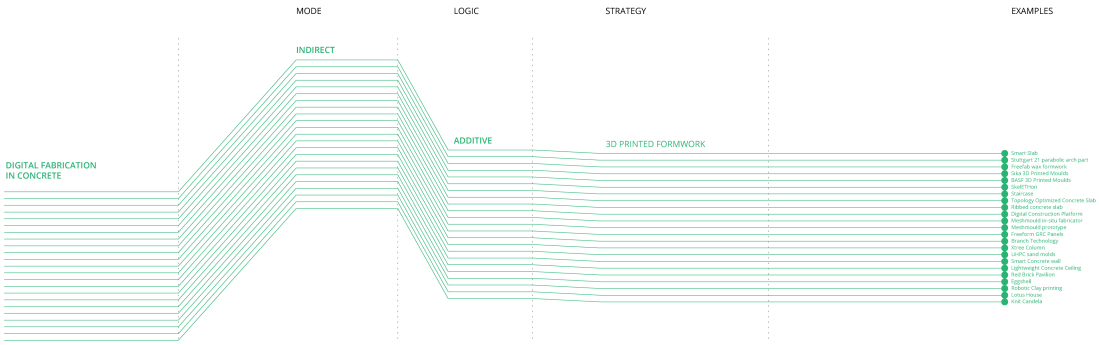


Figure 3.17: Indirect additive strategies for digital fabrication in concrete.

Indirect additive strategies for concrete architecture are based on the digital fabrication of formwork elements for subsequent concrete casting. A reading of existing literature points to two main strategies for using 3D printing in the fabrication of moulds for concrete construction. These strategies differ in design and usage of the produced moulds in the concrete casting process. As such, considering their application, 3D printed moulds can be used as:

1. 3D printed temporary formwork
2. 3D printed lost formwork

3D Printed temporary formwork

Although more commonly seen as direct concreting strategies, additive fabrication technologies have also been explored in indirect settings, specifically, in the printing of moulds or formwork liners. In these cases, conventional filament extrusion 3d printers, robotic or gantry extrusion printing systems or industrial large-scale particle-bed printing systems are used to produce customized moulds for concrete casting in various printing materials. These can be complete or partial mould pieces which can be used as rigid formwork elements. After printing, mould pieces are usually assembled, coated with release agents and cast with a concrete mix. After curing, the moulds are removed and discarded or recycled.

Depending on the printing technology and characteristics of the desired parts (size, geometry, mechanical properties, reusability, etc.) the mould elements can be produced from a variety of



Figure 3.18: Temporary 3D printed formwork examples: a) 3D printed sand formwork for UHPC spatial lattice; b) "Smart Slab", a topologically optimised precast slab structure with its underside cast on 3D printed moulds (particle bed 3D printing); c) a precast prototype wall section using a 2-part, 3D printed mould (FDM extrusion); d) 3D printed mould parts for a topologically optimised stair element.

substances. Moulds from materials such as casting sand (particle bed systems) and 3D printing thermoplastics such as PLA and ABS (extrusion systems) can currently be found in research and industrial applications. At an architectural level, several built academic prototypes have already been developed, exploring the design and constructive implications of 3D printed formwork at different scales. In one of the first such prototypes, in 2014, researchers at the Bartlett School of Architecture in conjunction with EZCT Architecture, designed and built complex Ultra High Performance Concrete (UHPC) spatial lattice structures, using 3D printed temporary sand moulds (Figure 3.18 a). In this case the researchers used industrial sand particle-bed 3D printers from Voxeljet to produce 252 small-scale formwork components. After fabrication, the printed elements were coated with a release agent and cast with a UHPC mix with reinforcement fibers to produce the final prototype (Morel and Schwartz, 2015). Using the same technologies, in the Smart Slab project, in 2017, researchers from the Digital Building Technologies Group at ETH Zurich, built a customized slab system, assembled on-site, at the DFAB house in Switzerland (Figure 3.18 b). The 22 x 12 m ceiling was composed of 27 precast and post tensioned elements which were cast using 3D printed temporary sand formwork (Meibodi and Leschok, 2018).

FDM based extrusion processes have also been used in several recent academic prototypes of temporary concrete formwork and are currently in development in industrial settings. For instance, in 2018, BigRep and the NOWlab group built a "Smart Concrete Wall" prototype, featuring a hexagonal freeform geometry with variable hexagonal openings (Figure 3.18 c). The wall section was cast using 3D printed formwork sections produced in a large-scale filament extrusion 3D printer. In 2019, researchers at the ETH Zurich, with the support of BASF, built a freeform stair step prototype, also using an extrusion based FDM 3D printer (Figure 3.18 d). The formwork for each step prototype was necessarily discretized in six parts to fit the printing envelope and avoid additional auxiliary support structures during printing, which took between 24 to 48 hours to complete (Jipa et al., 2019).

3D Printed lost formwork

3D printing of lost or stay-in-place formwork, presents a slightly different approach to concrete construction with additive technologies. Contrary to the previous strategy, in such cases the printed formwork becomes a permanent part of the finished concrete elements. This can be achieved using the same printing technologies mentioned above such as the extrusion of polymers, cement and clay mixes or particle-bed systems.

Similar to the structural prefabrication with ferrocement of Nervi, detailed in subsection 2.3.3 - Composition, 3D printing can operate on 2 levels for the production of lost formwork: an exterior shell or an interior form defining mesh. In the first case, 3D printing can be used to print a casting surface or exterior shell that becomes permanently embedded after pouring a structural concrete mix. This was exemplified in several prototypes of load-bearing concrete slabs, developed at the ETHZ in 2017, built using 3D printed sand moulds, cast with ultra-high-performance, fiber-reinforced concrete (UHPFRC) (Meibodi et al., 2017; Ruffray et al., 2017) (Figure 3.19 a). In this case, the researchers took advantage of the geometric possibilities granted by particle-bed printing systems to design formally optimized slabs with an intricate branching topology that minimized the use of materials for the specified mechanical behavior.

Another research, proposing 3D printing of lost formwork was developed at the Massachusetts Institute of Technology (MIT), where researchers from the Mediated Matter Group developed a 6-axis mobile robotic platform for the 3D printing of concrete formwork. The system, named "Digital Construction Platform" (DCP), was able to extrude in a 5cm layered process, the formwork for a hemi-ellipsoidal dome of 14.6m in diameter, in 48 hours (Figure 3.19 b). The stay-in place formwork of this process is similar to insulated concrete forms (ICF), providing thermal

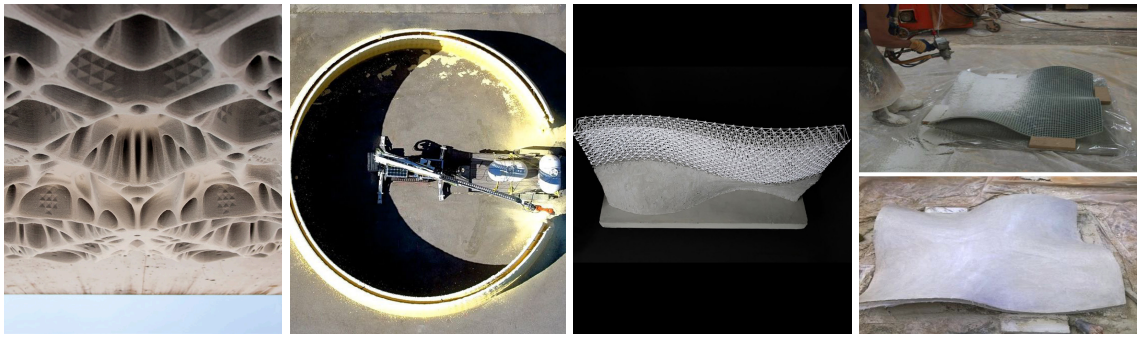


Figure 3.19: 3D printed lost formwork examples: a) underside detail of a UHPFRC slab prototype, with exterior stay-in-place 3D printed sand formwork (binder jetting); b) permanent, exterior 3D printed PU foam formwork for a concrete dome (extrusion); c) "Mesh Mould" - a 3D printed freeform interior mesh for a wall prototype; d) 3D printed freeform mesh for a GRC panel.

insulation for an interior concrete structural core, and was therefore not developed for apparent concrete structures.

In the second case, additive technologies can be used to produce metal or plastic wire meshes that act simultaneously as reinforcement and lost formwork for concrete structures. Early prototypes of the Mesh Mould project at ETHZ in 2014 (Hack et al., 2014) (Figure 3.19 c) as well as Branch Technology's Cellular Fabrication system demonstrate the possibility of building concrete wall segments by extruding a dense mesh or lattice-like structure that can be packed with an adequate concrete mix (Boyd, 2019). This strategy was further developed in the Mesh Mould project, substituting the polymer extrusion with the robotic production of a steel wire mesh, used in the Mesh Mould wall prototype also built at the D-FAB house (Hack et al., 2017). Finally, similar strategies can be found for 3D printing of meshes for freeform Glass Fiber Reinforced Concrete (GFRC) panels (Castañeda Vergara et al., 2017) (Figure 3.19 d).

Although limited to the various sizes of specific printing systems, these solutions, benefit from the increased geometric freedom of 3D printing when compared to subtractive or formative processes. Moreso in the case particle bed systems and binder jetting as they allow for even more intricate geometric features such as cavities and cantilevered areas without the need of additional support materials during printing. These features make 3D printing of concrete moulds particularly interesting for medium-scale prefabrication of highly complex and differentiated components such as those resulting from the design of topologically optimized structures, acoustic surfaces or simply highly detailed ornamentation. Moreover, these strategies benefit from the opportunity of the added performativity of different printing materials, possibly achieving different outcomes in the formwork itself or the finished concrete element, in the case of apparent lost formwork. Properties such as material reusability, solubility for ease of demoulding or ther-

mal insulation can be explored using different printing materials.

Nevertheless, as with all 3D printing technologies, fabrication time is an important limitation to the use of additive technologies for formwork production. With variations from specific fabrication technologies and processes, most strategies presented here operate at most at ½ m2 per hour of production for the digital fabrication phase alone, often resulting in several days per mould part. While this is feasible for highly complex and customized building elements, it is unreasonable as an overall solution for concrete architecture. Although there are design solutions to offset this issue, such as part repetition and the combination with other strategies, 3D printing of formwork is as of yet an expensive and time consuming process.

3.1.2 Direct Processes: digital concrete fabrication

3.1.2.1 Direct subtractive strategies: milling, cutting and carving concrete

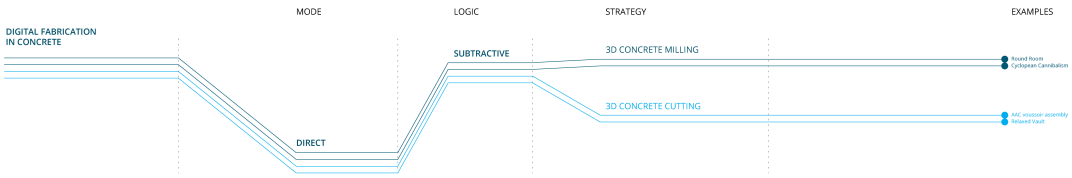


Figure 3.20: Direct subtractive strategies for digital fabrication in concrete.

Although subtractive technologies such CNC milling, water jet cutting and wire cutting have been more thoroughly studied for the production of formwork, in some cases, they have also been employed as processes to directly transform concrete, avoiding the time-consuming process of formwork fabrication. As such, direct subtractive fabrication of concrete architectural elements concerns the strategies that use digital fabrication processes operating on already hardened concrete, shaping it into architectural elements through cutting or carving operations. Considering the found examples, we consider strategies, similar to the previously defined as:

1. 3D milling of cured concrete components
2. 2D cutting of cured concrete components
3. 3D cutting or wire cutting of concrete components

Subtraction of concrete in itself, although apparently a not an ideal process considering the density and hardness of this material when cured, has been employed in the construction industry for decades. Particularly for maintenance or demolition operations. In effect, some of the first uses of subtraction processes applied to cured concrete were in bridge and road construction and maintenance (Hurst, 1955) and in the demolition of decommissioned concrete structures such as nuclear reactor shields) (Momber, 2011). In such cases, operations such as saw cutting, milling, waterjet or even laser cutting have been used, which established early on the feasibility, and simultaneous difficulty of transforming hardened concrete.

In the construction industry, digital fabrication using subtractive processes is also used to directly shape concrete elements in large scale precast facilities and standardized operations. Tools

such as multi axis CNC milling stations, CNC saws and robotic arms are used in digitally assisted processes for cutting, shaping, engraving, polishing and finishing rough concrete surfaces and edges in industrial settings (Van Acker, 1996), (Breton, 2020), (Thibaut, 2021) (Figure 3.21).



Figure 3.21: Direct subtraction of concrete: a) 3D milling (Cyclopean Cannibalism); b) 2D cutting (Cyclopean Cannibalism).

On another hand, in the field of architectural research, direct subtractive processes such as those discussed thus far were initially subject of research in conjunction with other non-formable materials such as stone for, which subtraction is the only transformation solution. Recent works such as Carrara Robotics (2014), the Armadillo Vault (2016), and Quarra Cairn (2017) demonstrated the architectural potential of digitally enabled direct subtraction of hard materials using abrasive wire cutting, CNC saws and robotic milling.

Although not as directly applicable in the construction practice as other methods presented before, there is active architectural research exploring the use of direct subtractive digital fabrication technologies for the production of architectural designs with concrete. Most of the examples found, use such methods for the construction of modular elements of variable geometries for complex assemblies, out of standardized stock materials, mimicking the three strategies found for subtractive formwork production but applied directly to concrete or concrete-like elements: 3D concrete milling, 2D concrete cutting and 3D concrete cutting.

One interesting use case is the design and construction of thin-shell voussoir vaults which were explored in small scale academic prototypes such as the Relaxed Vault (2012) and the Round Room projects (2014) by Matter Design, using Autoclaved Aerated Concrete (AAC) blocks

(Kaczynski et al., 2011; Clifford and McGee, 2015) (Figure 3.22 a,b)). AAC is an expanded concrete product which is used as a lightweight building block with thermal and acoustic properties. AAC also has a much lower density and compressive strength compared with traditional concrete which facilitates its use in conjunction with subtractive digital fabrication technologies such as robotic milling, robotic diamond wire cutting and water-jet cutting which were used in the mentioned works, combining 2D and 3D Cutting operations.



Figure 3.22: Examples of direct subtractive digital fabrication strategies: a) "Relaxed Vault", by Wesley McGee, 2012; b) "Round Room" by Matter Design Studio, 2014; c) "Cyclopean Cannibalism" by Matter Design Studio, 2017.

More recently, the Cyclopean Cannibalism wall prototype (2017) also by Matter Design (Figure 3.22 c)), applied this approach to actual concrete elements. In this project, a 6.6 meters by 2.3 meters modular wall prototype was built from concrete rubble, repurposed through the use of direct subtractive processes. The wall blocks were obtained from various sources and shaped into precise fitting elements using a combination of robotic sawing, milling and manual work, following an overall shape defined by a generative algorithm which minimized the generation of waste. Most of the digital fabrication operations were of 2D cutting and 3D milling. The finished blocks were then assembled into a self-sustaining wall, following the traditional construction technique of cyclopean masonry (Clifford and McGee, 2018). In this case, the direct subtractive process was fundamental as the only method possible of transforming the existing stock material and thus enabling this sustainable approach.

As a whole, direct subtractive digital fabrication processes seem to be a more natural approach to other materials which aren't naturally mouldable. Considering the time and energy expenditures necessary to process concrete in this way, its use can be prohibitive if not justified by other avenues such as repurposing. Another possible avenue is in more dedicated operations

which involve minimal material removal and not overall shaping of forms. This was the case of some of the operations of the Cyclopean Cannibalism project and also in formwork moulding processes already mentioned in (subsubsection 3.1.1.2) - Dynamic Formwork, which used the precision of milling to achieve more precise finished edges than the ones possible through casting (Peters et al., 2017).

In terms of geometrical freedom, as all milling processes, freeforms are possible to obtain in theory, using direct subtraction of concrete. In practice, sawing and flank cutting are more optimized processes, resulting in a language more associated with planar and ruled surfaces.

3.1.2.2 Direct formative strategies: moulding concrete

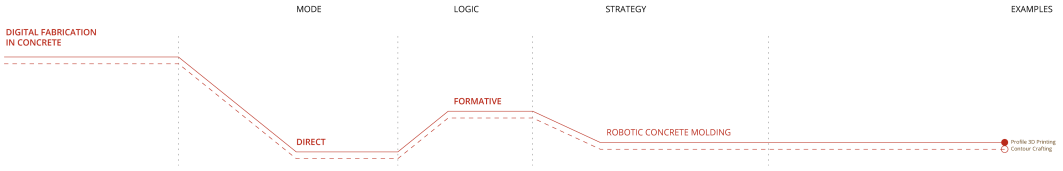


Figure 3.23: Direct formative strategies for digital fabrication in concrete.

Although it is generally used with naturally ductile materials such as wood or metal, digital fabrication using direct formative processes can also be used for concrete construction. In this context, the term *robotic concrete moulding* is used to describe such cases, where concrete is directly formed into shape while its still ductile, during its curing process. This is done through the use of digital fabrication technologies, such as robotic arms, equipped with specially designed end-tools.

In many digital fabrication processes mentioned thus far, the material properties of concrete play central roles to their success. Properties such as the size of aggregates, water-to-cement ratios, etc. influence among other characteristics, how wet concrete behaves when deposited or in reaction to external forces in the casting process, thus having important consequences on all aspects of the fabricated concrete elements. Usually this is an issue to be considered when designing concrete mixes, for instance, in concrete 3D printing where the extruded material must be fluid enough to be pumped, but must also maintain its layer shape.

Another key material feature of concrete is its curing process which allows for some movement after an initial setting time, before being fully hardened. This material property is in some cases used to produce concrete elements in flat surfaces which are bent into position after an initial hardening is achieved, avoiding the need for more complex moulds and other issues. A parallel example can also be found in the use of running moulds, for architectural features in cement and plaster. In these cases, instead of being cast into a mould, the wet material is deformed by the use of a profiling tool, running along a straight path.

Some digital processes already use these material features of concrete in their fabrication strategies, when including formwork. For example, some dynamic formwork strategies mentioned in (subsubsection 3.1.1.2) - Dynamic Formwork, that do not use additional intermediate formwork, but lay concrete directly on the actuated surface, include a curing period before the surface is digitally deformed to the desired geometry. This allows for the initial use of an adequately

fluid mix to fill the mould while afterwards preventing the concrete to slide and accumulate on the lower parts of the moulding table through the effect of gravity, resulting in a homogenous material thickness.

Although not a very active research topic, the strategy of directly changing the shape of an existing concrete volume through digital processes has also been explored in academia. The concept of robotic concrete forming, works in a similar fashion to a sculptor moving material on a piece of clay or plaster. In this case instead of a manual process, a preset volume of wet concrete with an adequate workability is sculpted through the use of a robotic arm, with a custom-made end tool. One early, although tangential, example is the use of trowels in the Contour Crafting process to achieve smooth surfaces (Zhang and Khoshnevis, 2009) (Figure 3.24 a).



Figure 3.24: Direct moulding of concrete elements: a) Early prototype of extrusion nozzle in the Contour Crafting process, containing a troweling mechanism for surface moulding; b) "Profile-3D-Printing" process, showing a wet concrete base being deformed with a robotic end-effector; c) Panel like element after curing.

Following previous experiments with other materials (Bard et al., 2012), a research team at Carnegie Mellon University, developed a digital fabrication process, using this strategy, for the design and pre fabrication of concrete panels. The self-titled Profile-3D-Printing process incorporates two phases: the rough deposition of a volume of wet concrete and the subsequent shaping of the surface geometry, using a profiling tool attached to a 6-axis robotic arm. The tool is sweep along the wet surface of the concrete volume in several passes, and the final concrete geometry is a combination of the tool shape and the defined paths. Using this process, several panels with variable surface geometries, designed for thermal efficiency were built by combining different tool geometries and tool paths (Figure 3.24 b,c). Considering the main role of the wet concrete moulding in the finished components, we consider this approach mainly a formative process

rather than an additive one (Bard et al., 2019).

One of the most interesting aspects of these robotic concrete forming strategy is its relation with craft-based processes. Like the traditional processes that they expand, there is a special link between tool and design. In other processes, such as CNC milling, the entirety of the resulting form is predesigned in a 3D model and faithfully recreated by the robotic tool. In robotic concrete forming, the final design geometry emerges from the relation between tool and process. This creates a robotic process with a specific architectural vocabulary, different from others. Consequently, this is also one of its main limitations to more widespread use as there are limits to possible geometries, when compared with the possibility of generic double curved surfaces and available detail resolutions of other processes such as milling and 3D printing.

3.1.2.3 Direct additive strategies: printing concrete

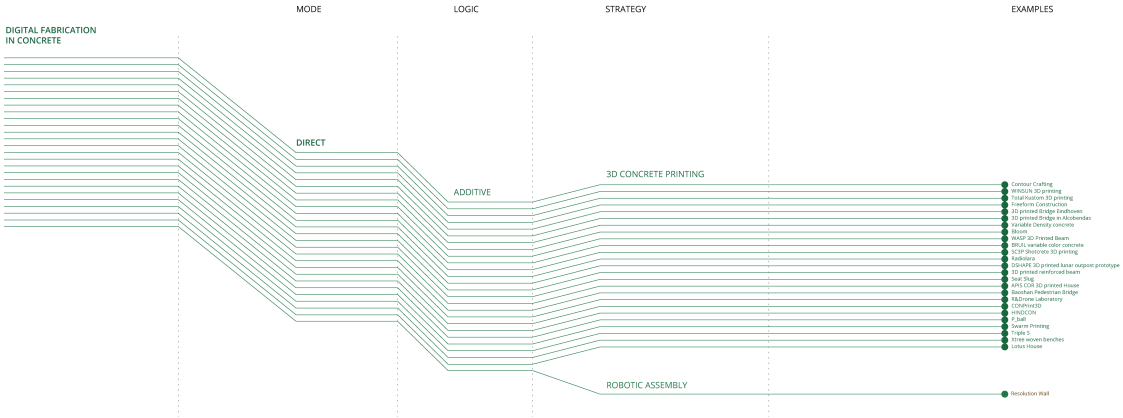


Figure 3.25: Direct additive processes for digital fabrication in concrete.

Considering the high costs, manpower and material waste usually associated with the fabrication of formwork for non-standard concrete architecture (Nawy, 2008b), several research groups have focused on finding alternative solutions to this problem. One of the most developed solutions in this regard is the production of concrete architectural elements by 3D printing, using large-scale, cement-based additive manufacturing technologies. These processes are usually referred as 3D concrete printing (3DCP).

In general terms, 3DCP can be described as the process of direct and precise deposition of a wet concrete mix or hardening of a particle-based matrix, in a layered process, through the use of a computer-controlled mechanism, informed by digital data.

According to international standards, additive manufacturing (AM) processes can be divided into several subcategories considering their interaction with the printed material (ISO, 2021). In the case of 3D concrete printing in, the last two decades, several different processes have been developed, mostly falling into 3 main categories, each with unique architectural consequences:

1. Concrete extrusion
2. Particle-bed 3D printing
3. Robotic spraying

Concrete Extrusion

Material extrusion in the scope of an additive manufacture technique for concrete printing, can be defined as a process through which a concrete mix is pumped through a nozzle and deposited to achieve a desired form. The first patented concrete 3D printing process was an extrusion process and was developed by Behrokh Khoshevis at the University of South California, in 1995 (Khoshevis, 1996). The process, named Contour Crafting, involved the controlled continuous extrusion of a specially engineered concrete mix, layer by layer, using a computer controlled, 3-axis gantry with a mounted extrusion head (Khoshnevis and Dutton, 1998). Different construction approaches were studied, including printing exterior shells and infill in succession and printing mostly hollow concrete structures for reinforcement placement and filled with regular concrete. This process was used to build walls and other architectural elements, postulating the possibility of on-site printing of complete concrete buildings (Hwang and Khoshnevis, 2004)(Figure 3.26 a).



Figure 3.26: Examples of concrete printing, using extrusion systems: a) wall segment using the Contour Crafting process, by Behrokh Khoshevis at the University of South California; b) a double-curved concrete panel, using the Freeform Construction system, by Richard Buswell at the University of Loughborough; c) Baoshan bridge, Shanghai, 2019.

Since these initial studies, several other developments followed, based on the contour crafting technique of material extrusion, improving printing resolutions, extrusion and control techniques, mix composition, etc. Relevant work was done in academia at the University of Loughborough in the freeform construction system showcasing, among others, a 3D printed double-curved façade panel system (Buswell et al., 2007; Lim et al., 2016) (Figure 3.26 b). Since then, in industrial settings such as the Chinese company WINSUN, the American based Total Kustom and Apis Cor, advances were made in large scale printing of complete buildings albeit with simple extrusion geometries, such as shelters, small bridges and other small structures and build-

ings. Recently, 2 small scale bridges have been built using this process. In 2017, a 6.5 m by 3.5 m bicycle bridge was 3D printed at the Eindhoven University of Technology, a 4-axis computer-controlled gantry with an extrusion nozzle. The bridge span was divided into 7 curved extrusion segments which were printed, assembled and pre-stressed off-site and finally mounted on-site. The printing process was completed in 48 hours for all segments (Salet et al., 2018). Another pedestrian arch bridge was completed in 2019 in Shanghai, China, composed of 44 individual voussoirs, without other structural reinforcements (Xu et al., 2020) (Figure 3.26 c).

Recently, the advantages of 3D printing of concrete materials through extrusion, have also been studied for their potential to enable concrete construction in remote and low resource conditions, such as is the case of off-world habitats and other construction elements in similar conditions (Meisel et al., 2022).

Most research examples presented thus far are focused on achieving large-scale constructions with satisfying structural properties. Notwithstanding, some examples can also be found that study the possibility of more expressive features in concrete printing such as surface textures and material colors. One such example is the 3.72 m by 2.7m shelter by Siam Research and Innovation Company (Prasittisopin et al., 2018), or the Woven benches by XtreeE and Design Studio 7.5 (Xtree, 2020), exploring the properties and behavior of concrete layers during printing to achieve textural qualities (Figure 3.27 a).

Moving from surface qualities to material composition, Neri Oxman, at the Massachusetts Institute of Technology (MIT) Mediated Matter Lab, was able to 3D print concrete components with functionally graded properties, by incorporating foaming agents in the concrete mix, achieving concrete elements with variable densities throughout one single component (Figure 3.27 b). This performative objective for material gradation was similarly studied at UPenn, by combining cement extrusion techniques and cork as a lightweight aggregate to produce functionally graded concretes (Craveiro et al., 2020).

Moving from performative to aesthetic intentions, the Dutch concrete company Bruil and RAP Technologies demonstrated in small-scale prototypes, the possibility of 3D printing concrete with other variable compositions, creating interesting color gradients in 3D printed concrete elements (Figure 3.27 c).

Although promising, extrusion 3D printing systems also have significant drawbacks regarding their possible design language. Currently, extrusion layer resolutions range from less than 1mm to over 10cm (e.g. CONPrint3D (Mechtcherine et al., 2019)). Therefore, the architectural freedom of design is limited to the minimum size of these layers. Furthermore, with the exception



Figure 3.27: Examples of extrusion-based 3D printing processes focused on the exploration of new material qualities: a) Shelter structure by Siam Research and Innovation Company, exploring the textural qualities of extruded concrete; b) variable density concrete prototypes, Neri Oxmann, MIT; c) detail of wall prototypes of concrete extruded with a variable color by Bruil and RAP Technologies.

of Contour Crafting which employs trowels for smoothing the extrusion process, the printing layers are usually apparent in the finished surfaces which can be undesirable. A further limitation to geometric freedom of these processes comes from the lack of support during printing. As support is generally only maintained through the contact of the previous layer, it is difficult to print features such as overhangs, voids and double curved surfaces with high degrees of curvature without additional support structures. To address this issue, some 3D printing experiments develop combined processes, using formwork in addition to extrusion 3D printing, such as the De|Stress Pavilion case mentioned in (subsubsection 3.1.1.2) - Formwork Moulding.

Particle bed 3D Printing

Contrary to extrusion processes, where concrete is premixed and printed in a wet state, particle bed systems are defined by the use of raw, dry materials. These materials are prearranged to occupy a specified area in a construction platform where a computer controlled robotic arm or gantry system selectively deposits a fluid binding agent that fuses the raw materials in selected areas. This process is repeated layer by layer, using the digital information of a sliced 3D model to complete the desired form, in a similar fashion as regular desktop 3D printers. Large scale sand-based particle-bed 3D printers, such as the Voxeljet VX4000, already mentioned in (subsubsection 3.1.1.3) - 3D Printed formwork, usually produce brittle components with low compression and tension resistance and are therefore not directly suited for self-supporting components. Nevertheless, advances have been made in this regard, incorporating other materials in particle beds, such as cement, allowing for the direct digital fabrication of concrete-like architectural elements, such as walls, freeform façade elements, bricks and even full-scale constructions

(Lowke et al., 2018).

One such example is the D-Shape printer, developed by Enrico Dini in 2006 (Dini et al., 2005; Ceccanti et al., 2010). One of the first printed objects using this system was the Radiolara Pavilion, designed by architect Andrea Morgante in 2008. The 3m by 3m by 3m monolithic pavilion, was subdivided in 400 5mm layers and printed in one week by the first large scale d-shape printer (Morgante, 2011). Since then, numerous prototypes have been built as well as the first 3D printed pedestrian bridge, in Alcobendas, Spain, using the same process (Figure 3.28).



Figure 3.28: Early particle bed system, D-Shape: a) detail of a D-shape printer during the printing process; b) Radiolara Pavilon, by Shiro Studio, 2008 and D-Shape; c) pedestrian bridge in Alcobiendas, Spain.

At a smaller scale, interesting examples can also be found in the works of Rael San Fratello Architects and Emerging Objects. The Seat Slug bench (2011) (Figure 3.29 a)), the PBall sculpture (with Andrew Kudless, 2012) (Figure 3.29 b)) and the Bloom Pavilion (2015) (Figure 3.29 c)), a self-supported academic pavilion, composed of 840 unique 3D printed blocks (Figure 3.29). The bonded particle-bed material used was composed mainly of Portland cement, achieving surface characteristics similar to concrete (Fratello, 2020). While not large-scale or structural solutions, the installations developed, express the design possibilities of particle-bed, cement-based 3D printing systems for the prefabrication of assemblies of variable elements with an extremely high resolution and complexity of geometrical features. In some analyzed cases, such as the PBall sculpture, printing resolution was such that some digital 3D model characteristics, such as small mesh facets become apparent in the finished pieces.

As was already mentioned, particle bed processes have the ability to produce very complex geometries. Large scale printers with cementitious materials such as the D-Shape printers, can now achieve particle resolutions of up to 0.2mm (Lowke et al., 2018, 2020), allowing for the description of very fine details. Moreover, the support granted by the unbound particles of previous layers enable the design of features not possible with other 3D printing techniques.



Figure 3.29: Cement-based 3D printing examples of small-scale components: a) Seat Slug, by Real San Fratello Architects, 2011; b) PBall sculpture, by Andrew Kudless, 2012; c) Bloom Pavilion by Real San Fratello Architects, 2015.

Features such as steep inclined and curved surfaces, arches, vaults, cantilevered elements and interior voids can easily be used in particle bed 3D printed designs.

On the other hand, one significant constraint of particle bed 3D printing, when compared with other digital fabrication processes already mentioned is the limitation on component dimensions to the enclosed construction volume of the specific printing systems, lacking the possibility of onsite construction of other processes. Also, increases in fabrication resolution and volume naturally have a corresponding increase in fabrication time.

Robotic Spraying

A different strategy for the direct 3D printing of concrete architectural elements is through robotic spraying. As with other strategies presented thus far, where traditional construction methods are revisited with new technologies, this strategy is at its core, a digitally enhanced version of the traditional manual shotcrete and GFRC spraying processes. Regarding GFRC automation, as early as 1993, research was conducted in Spain, by the Division of Systems and Automation Engineering (DISAM - División de Ingeniería de Sistemas y Automática) of the Polytechnic University of Madrid, together with the company Dragados y Construcciones S/A. Between 1993 and 1995, researchers developed and implemented an automated plant for the production of GFRC facade panels, using a robotic arm guided by CAD information, to replace the manual labor of spraying concrete onto the mould (Balaguer et al., 1993) (Figure 3.30 a).

More recently, researchers at the Institute of Structural Design (ITE) at Braunschweig University of Technology, developed the Shotcrete 3D Printing process (SC3DP), a robotically assisted



Figure 3.30: Robotic spraying of concrete elements: a) robotic prototype for automated GRC spraying by Dragados y Construcciones, 1995; b) Shotcrete 3D printing process (SC3DP) at TU Braunschweig; c) prototype double-curved wall element, using the SC3DP process.

shotcrete technology for the direct digital fabrication of concrete structures without the use of formwork (Herrmann et al., 2018). In contrast to concrete extrusion processes, with SC3DP it is possible to deposit the concrete mix not only in layers, but also spatially, in any direction available to the robotic arm. This feature enables an increase in geometrical freedom and enables the use of reinforcement structures within the printing envelope. Research is still in the first stages, but built prototypes have been developed for wall structures and prefabricated components for complex variable modular concrete structures (Hack et al., 2019; Hack and Kloft, 2020) (Figure 3.30 b,c).

As a direct additive process, one of the major benefits of SC3DP is that it does not require the production of formwork. Also, when compared with other additive processes, it presents an improvement in geometric freedom to concrete extrusion processes, considering the possibility of depositing material at different angles, while not achieving the level of particle-bed 3D printing. Another key issue is the complexity of control for such processes. Currently, concrete structures built by robotic spraying exhibit a rough surface, with limited boundary precision. This imposes the use of additional surface smoothing and boundary cutting operations, which impose additional layers of complexity and build time to this process.

3.1.3 Critical Analysis

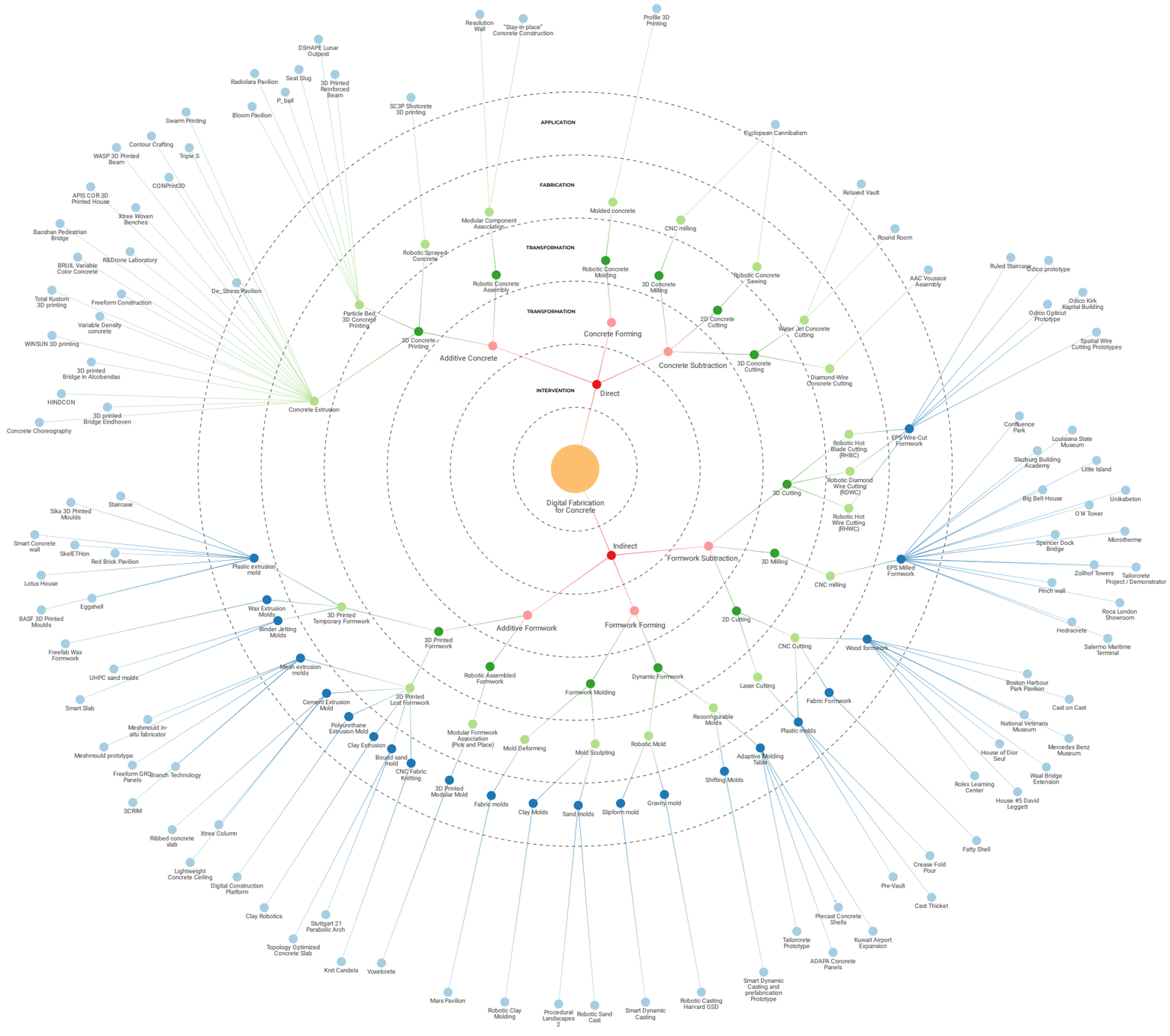
In the previous section, a large number of digital fabrication processes were presented, explained and separated into similar categories. Several works were used to exemplify each category, which mapped into a network, define the digital fabrication diagram shown in Figure 3.32.

In order to derive conclusions from the previous analysis and considering the inherent differences between all of the presented processes, it is relevant to review all of them in a similar framework to conclude their main strengths and weaknesses. Figure 3.31 illustrates the findings for all concrete digital fabrication processes resulting from a qualitative comparative analysis. This analysis is performed for each digital fabrication strategy as a whole, not considering particular examples of its use. It is focused on evaluating the potential of each process through the use of seven relevant categories, explained below, with different values in parenthesis and the main conclusions in bullet points.

DIGITAL FABRICATION STRATEGIES FOR CONCRETE	FORM	SURFACE	MATERIAL	FABRICATION TIME	MANUAL LABOUR	PROCESS COMPLEXITY	APPLICATION
3D MILLING	3D ●●●●	smooth ●●●	very high ●●●●●	hours ●●●	assembly and/or post processing ●●●	low tech ●	In-situ/Precast
2D CUTTING	limited 3D ●●●	very smooth ●●●●	medium ●●●	hours ●●●	on-site operations ●●●●	low tech ●	In-situ/Precast
3D CUTTING	limited 3D ●●●	smooth ●●●	medium ●●●	seconds ●	assembly and/or post processing ●●●	low tech ●	In-situ/Precast
DYNAMIC FORMWORK	limited 3D ●●●	very smooth ●●●●	low ●●	minutes ●●	minimal/assembly ●●	high tech ●●●	Precast
FORMWORK MOLDING	3D ●●●●	homogenous texture ●●	medium ●●●	minutes ●●	assembly ●●	medium tech ●●	Precast
3D PRINTED TEMPORARY FORMWORK	3D + undercuts ●●●●●	smooth ●●●	medium ●●●	hours ●●●	assembly ●●	high tech ●●●	Precast
3D PRINTED LOST FORMWORK	3D + undercuts ●●●●●	smooth ●●●	very low ●	hours ●●●	assembly ●●	high tech ●●●	Precast
CUT / MILLED CONCRETE	curved 1D ●●	homogenous texture ●●	low ●●	hours ●●●	none ●	medium tech ●●	Precast
MOLDED CONCRETE	limited 3D ●●●	homogenous texture ●●	very low ●	minutes ●●	none ●	high tech ●●●	Precast
3D PRINTED EXTRUDED CONCRETE	limited 3D ●●●	rough ●	very low ●	hours ●●●	none ●	high tech ●●●	In-situ/Precast
3D PRINTED SPRAYED CONCRETE	limited 3D ●●●	rough ●	very low ●	hours ●●●	assembly and/or post processing ●●●	high tech ●●●	In-situ/Precast
3D PRINTED POWDER BOUND CONCRETE	3D + undercuts ●●●●●	smooth ●●●	very low ●	hours ●●●	none ●	high tech ●●●	Precast

Figure 3.31: Analysis of digital fabrication strategies for concrete construction based on 6 qualitative parameters: form, surface, material, fabrication time, manual labour, process complexity and application.

Figure 3.32: (interior) Digital fabrication in concrete: mapping of different examples of digital fabrication strategies for concrete elements, using the four parameters developed in the previous classification: intervention type, transformation logic, digital fabrication strategy and application and a further subdivision in application subtype/material.


Digital Fabrication for Concrete
Intervention Mode
Transformation Logic
Digital Fabrication Strategy
Application
Digitally fabricated element
Example
APPLICATION
FABRICATION
TRANSFORMATION
TRANSFORMATION
INTERVENTION
Direct
Indirect
Additive Concrete
Concrete Forming
Concrete Subtraction
Additive Formwork
Formwork Forming
Formwork Subtraction
Concrete Extrusion
Particle Bed 3D Concrete Printing
3D Concrete Printing
Robotic Sprayed Concrete
Modular Component Association
Robotic Concrete Assembly
Molded concrete
Robotic Concrete Molding
3D Concrete Milling
CNC milling
2D Concrete Cutting
Robotic Concrete Sawing
3D Concrete Cutting
Water Jet Concrete Cutting
Diamond-Wire Concrete Cutting
Cyclopean Cannibalism
Relaxed Vault
Round Room
AAC Voussoir Assembly
Profile 3D Printing
Resolution Wall
"Stay-in-place" Concrete Construction
DSHAPE Lunar Outpost
Radiolara Pavilion
Seat Slug
3D Printed Reinforced Beam
P_ball
Bloom Pavilion
SC3P Shotcrete 3D printing
Swarm Printing
Contour Crafting
WASP 3D Printed Beam
Triple S
CONPrint3D
APIS COR 3D Printed House
Xtree Woven Benches
Baoshan Pedestrian Bridge
BRUIL Variable Color Concrete
R&Drone Laboratory
De_Stress Pavilion
Total Kustom 3D printing
Freeform Construction
Variable Density concrete
WINSUN 3D printing
3D printed Bridge in Alcobendas
HINDCON
3D printed Bridge Eindhoven
Concrete Choreography
Ruled Staircase
Odico prototype
Odico Kirk Kapital Building
Odico Opticut Prototype
Spatial Wire Cutting Prototypes
EPS Wire-Cut Formwork
Robotic Hot Blade Cutting (RHBC)
Robotic Diamond Wire Cutting (RDWC)
Robotic Hot Wire Cutting (RHWC)
3D Cutting
3D Milling
CNC milling
EPS Milled Formwork
Confluence Park
Louisiana State Museum
Slazburg Building Academy
Little Island
Big Belt House
Unikabeton
O 14 Tower
Spencer Dock Bridge
Microtherme
Zollhof Towers
Tailorcrete Project / Demonstrator
Pinch wall
Roca London Showroom
Hedracrete
Salermo Maritime Terminal
Staircase
Sika 3D Printed Moulds
Smart Concrete wall
SkelETHon
Red Brick Pavilion
Lotus House
Eggshell
BASF 3D Printed Moulds
Freefab Wax Formwork
Plastic extrusion mold
Wax Extrusion Molds
Binder Jetting Molds
3D Printed Temporary Formwork
UHPC sand molds
Smart Slab
Mesh extrusion molds
Cement Extrusion Mold
Polyurethane Extrusion Mold
Clay Extrusion
Bound sand mold
CNC Fabric Knitting
3D Printed Lost Formwork
Meshmould in-situ fabricator
Meshmould prototype
Freeform GRC Panels
Branch Technology
SCRIM
Ribbed concrete slab
Xtree Column
Lightweight Concrete Ceiling
Digital Construction Platform
Clay Robotics
Topology Optimized Concrete Slab
Stuttgart 21 Parabolic Arch
Knit Candela
Voxelcrete
3D Printed Formwork
3D Printed Modular Mold
Modular Formwork Association (Pick and Place)
Robotic Assembled Formwork
Fabric molds
Mold Deforming
Clay Molds
Mold Sculpting
Sand molds
Formwork Molding
Slipform mold
Dynamic Formwork
Robotic Mold
Gravity mold
Reconfigurable Molds
Shifting Molds
Laser Cutting
Adaptive Molding Table
CNC Cutting
Plastic molds
Fabric Formwork
Wood formwork
Mars Pavilion
Robotic Clay Molding
Procedural Landscapes 2
Robotic Sand Cast
Smart Dynamic Casting
Robotic Casting Harvard GSD
Smart Dynamic Casting and prefabrication Prototype
Tailorcrete Prototype
Precast Concrete Shells
Kuwait Airport Expansion
ADAPA Concrete Panels
Pre-Vault
Crease Fold Pour
Cast Thicket
Fatty Shell
Boston Harbour Park Pavilion
Cast on Cast
National Veterans Museum
Mercedes Benz Museum
House of Dior Seul
Rolex Learning Center
Waal Bridge Extension
House #5 David Leggett

Form: *complexity of achievable geometries in concrete elements, using a specific digital fabrication strategy (1D; 2D; limited 3D; 3D; 3D + undercuts).*

Form is the first central characterising aspect of a digital fabrication strategy as it directly discribes the possibility of achieving a specific desired geometry in concrete. Different processes have different geometrical constrains, regarding to the possibility of defining planar surfaces (1D), curved surfaces in one direction (2D), curved surfaces in two directions (3D), a limited subset of double curved surfaces (limited 3D) and the possibility or lack thereof of fabricating cantilevered, undercut or void sections (3D+Undercut).

- Maximum formal freedom in concrete architectural elements can be achieved with 3D printing of formwork and with direct 3D printing of concrete, when powder bed 3d printing is used. In such cases, double-curved surfaces, with cantilevered, undercut and void areas can generally be created.
- CNC Milling presents the second most capable process of creating geometrical complex elements with the ability to achieve freeform geometries with large or small curvature radii, with the added advantage of the existence of large-scale 3D milling technologies.
- There are several processes which generally have the possibility to achieve 3D surfaces, but with many limiting factors. 2D cutting of formwork can achieve 3D surfaces with limited curvature radii, considering the need to bend formwork materials; 3D cutting (RHWC) can achieve only ruled surfaces but with mostly unrestricted curvatures. Forming tables can produce 3D surfaces similar to CNC milling, with the added benefit of reusability but with much more limited curvatures, perimeter shapes and dimensions; 3D Concrete Printing technologies using extrusion or spraying are also limited in possible geometries and 3D curvature radii, due to the need of support between layers.
- Many specific processes such as the robotic slip-forming in the dynamic formwork category or the textile moulds in the formwork moulding category, are usually further limited to a specific design language tailored to each project.

Surface: *quality of finished surfaces using a specific digital fabrication strategy (rough; homogenous texture; smooth; very smooth).*

Surface quality is still one of the most relevant aspects of concrete architecture. Surface quality can range from a rough heterogenous finish, to a visible yet homogenous texture, to smooth and very smooth finishes. Generally speaking, smooth and homogenous surfaces are the most

desirable. Considering the nature of concrete as a casting material, smooth surfaces are more easily achievable when using formwork and more specifically when using smooth, waterproof formwork materials. Nevertheless, control over textural elements emerging from fabrication processes can also be a desirable quality.

- 2D cutting and Dynamic Formwork strategies generally grant very smooth concrete surfaces by using continuous, non-porous materials as formwork or formwork lining surfaces.
- 3D Milled and RHWC cut formwork (usually in EPS) can achieve smooth surfaces but only with the application of coatings and sanding procedures or with the use of other interface materials (e.g., plastic membranes, wood laminates).
- When this is not the case, apparent surfaces present the homogenous textures of the milled or wire-cut formwork material which can be explored in design solutions.
- 3D printed extruded concrete presents very rough textures as the deposition layers are usually visible. Nevertheless, when controlled, can produce interesting surface textures which can appear homogenous at larger scales.
- Some processes such as lost infill formwork and sprayed concrete do not generate smooth surfaces but assume complementary manual post-processing (troweling) of surfaces while wet which can lead to smooth finishes.

Material: *material waste generation in formwork or concrete production (very low; low; medium; high; very high).*

The level of material waste production is a relevant consideration in the general sustainability of a digital fabrication process. Material waste or its inverse, material optimization can be achieved in different stages of a digital fabrication process, either in reducing formwork production materials or in reducing the amounts of actual concrete used. This can be a design issue, but it can also be aggravated by the specific digital fabrication strategy employed.

- Additive processes produce the least waste materials. Not only they do not require formwork but also the possibility of realizing very complex shapes has the potential to reduce concrete usage in structurally and materially optimized designs.

- 3D printed lost formwork is the less wasteful solution involving the production of formwork, as expended materials become a part of the finished architectural elements.
- Dynamic formwork solutions also produce low amounts of waste materials, particularly when used in a precasting setup. When used as intermediary steps for the production of static formwork, it is dependent on the formwork material and its intrinsic reusability or recyclability.
- All other processes that use temporary formwork except for 3D milling are considered medium wasteful (2D Cutting, RHWC, Formwork moulding). Generally speaking, such processes assume some degree of material waste in the discarding of the formwork elements.
- 3D milling when used exclusively is considered to be the most wasteful process. It presents the same issues described for temporary formwork solutions but also involves the waste of a very large percentage of material in the subtractive production of formwork elements.
- Regarding the use of EPS formwork, RHWC has the opportunity to generate significantly less waste material when compared with CNC Milling as the cutting process allows for a better usage of the stock volume with minor wastage for similar end results.

Fabrication Time: *fabrication time per square or cubic meter of final element (seconds; minutes; hours).*

Fabrication time is one of the most relevant aspects of digital fabrication strategies for their potential integration into actual construction processes and is largely responsible for production costs. There is a large variation in digital fabrication processes, but they are presented here in a broad classification of fabrication time per square or cubic meter, in seconds, minutes or hours. Processes are directly compared in production time, ignoring the potential inherent advantage of direct processes in producing finished architectural elements.

- 3D printing processes are measured in hours per square meter of finished wall segments, either for direct 3D printing or 3D printing of moulds. A tradeoff is generally possible between production time and geometric resolution, with larger printing layers but this results in lower surface qualities.
- The fact that direct 3D printing processes bypass the need for a mould, is not considered to overcome the fabrication expedience of very fast processes that still require formwork

(e.g. RHWC). In some 3D direct printing processes, there are additional steps not generally considered, such as conventional casting of hollow segments and manual applications of reinforcement.

- As already mentioned in its subchapter, 3D miling is an excessively time-consuming process for formwork fabrication, also measuring in hours per square meter.

- Although 2D cutting is inherently faster than 3D milling, the need to cut several parts for substructures and casting surfaces, also results in several hours of machining per part.

- Formative shaping processes such as formwork moulding and direct concrete moulding are a large step up in terms of production times, being able to shape surfaces in minutes.

- Robotic Hot Wire Cutting technologies present the fastest fabrication times of all formwork processes, being able to shape double curved ruled surfaces in seconds, up to a couple of minutes per square meter, with the possibility of added time in other operations such as manual coatings.

Manual Labor: *amount of manual labor necessary for the digital fabrication process (minimal; assembly only; assembly + post processing; on-site specialized operations).*

While digital fabrication processes in general are characterised by their automated character, the process of creating architectural concrete elements, either in-situ or through prefabrication, entails several phases, some of which are not easily automated. As such, some digital fabrication processes require additional manual procedures such as assembly, post-processing operations (e.g. formwork coating) or other specialised operations. The amount of such manual labour is a relevant feature when discussing such processes, considering that they can greatly impact on production times and the need of additional manpower to achieve the full potential of a specific digital fabrication strategy.

- Direct processes, specifically Direct 3D printing of concrete structures using extrusion, imply in principle the least amounts of manual labor, particularly when used in on-site processes that don't require further assembly.

- 3D milling and 3D cutting (of EPS moulds) can be assembled directly after fabrication, but most commonly further manual coating and sanding of the moulds is required to achieve acceptable finishing qualities.

- 2D cutting of formwork components presents the most labor intensive process, requiring large amounts of manual labor to assemble cut parts into finished formwork, similarly to traditional formwork construction processes.

Process Complexity: *level of technological complexity and difficulty of adoption into existing processes and industry (low tech; medium tech; high tech).*

Although production speed, costs and material usage are important factors for the adoption of novel construction processes, the intrinsic complexity of a digital fabrication strategy can also be of great relevance when considering its applicability in a real-world scenario. Therefore, it is relevant to consider how complex is a specific digital fabrication strategy and how difficult its adoption can be outside of the academic research environment.

- All indirect subtractive processes for formwork fabrication are considered low-tech/easy adoption into existing construction processes. This is the case, considering two main factors. Firstly, the specific fabrication processes (i.e. 3D milling, 2D cutting and RHWC to a lesser degree) are well-known fabrication processes that have been used in the construction industry and others for several decades, with an established technological know-how that does not require specialised knowledge development. Secondly, these processes are mostly used to fabricate formwork elements that will generally be applied within other established construction processes and do not require entirely new construction strategies. For instance, 3D milled and RHWC EPS moulds can be directly used with standardised falsework elements in in-situ castings.

Application: *wether the analysed process is applicable in in-situ concrete casting or as precast solutions or both (in-situ; precast; in-situ/precast).*

Depending on the specificities of any digital fabrication process, irregardless of the example of its application and the specific forms developed through it, generally speaking all processes can be separated by their application. This differentiates digital processes that are tailored for in-situ monolithic construction, for prefabrication only or usable in both situations. Conclusions can thus be drawn about their adaptability and application for different architectural solutions.

- All indirect subtractive processes are adaptable as solutions for both in-situ and precasting solutions. The formwork elements resulting from 3D milling, 2D cutting and 3D

cutting are easily used as individual elements in precasting or as parts of continuous formwork solutions as show by the used examples.

- Indirect formative processes are mostly tailored for precasting in general and precasting of panel-like elements. Nevertheless, some examples have shown the use of both technologies as intermediate solutions for building sand and wax moulds which could in be used for in-situ casting.

- Indirect additive processes (3D printed formwork), are mostly solutions for precasting of concrete components, and only few examples were found that used some 3D printed mould parts in conjunction with traditional formwork systems for small complex details. One of the most relevant issues for this is related with a low resistance of 3D printed mould materials to the hydrostatic pressure of wet concrete, resulting in their application for more complex yet smaller components.

- Direct additive processes, depending on technology can be applied as in-situ or precasting solutions. While most concrete extrusion processes are presented as solutions for in-situ construction, some have also been shown to produce prefabricated components for assembly. The less resistant material resulting from particle-bed 3D printing, when used do directly print concrete, has usually been applied as a prefabrication methodology.

3.2 Expanded tectonics for digital concrete

The previous analysis presents a large picture of what is today technologically feasible. At the same time, the different applications of such contrasting processes also point to emerging tectonic qualities of concrete structures produced with digital fabrication tools. These can be expressed as an expansion of the previously mentioned tectonic dimensions of *form, surface and composition*. From the analysis of the previous examples in this conceptual framework we can form a picture of the potential emerging tectonic signifiers, characteristic of digitally fabricated concrete architecture.

Expanded Form

When considering the issue of *form*, we can identify two recurring overall themes, considering the previous separation between continuous and discontinuous logics of design and a third emerging one: a) complex 3D geometries, either smooth or detailed in monolithic or precast systems; b) small to medium-scale assemblies of variable modular components; c) digital process-specific formal vocabularies (Figure 3.33)

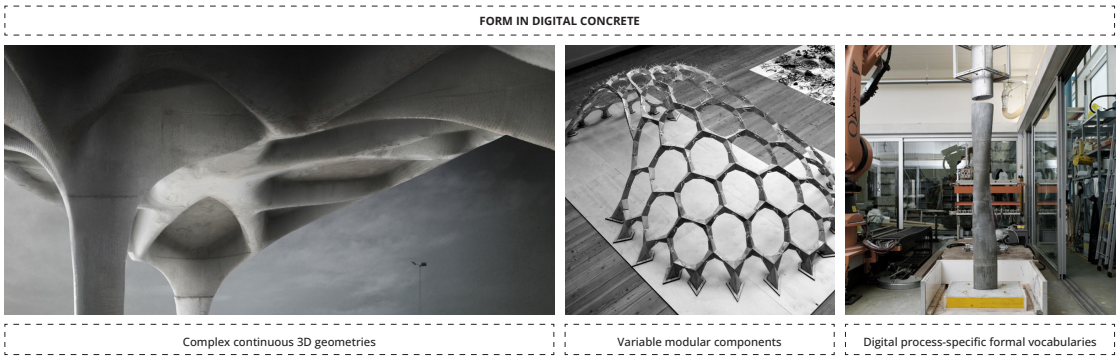


Figure 3.33: Form in digitally fabricated concrete: a) complex continuous 3D geometry, resulting from a topological optimisation design process in the unikabeton prototype (Dombernowsky and Søndergaard, 2011) ; b) variable modular components, using laser cut formwork, in the revault pavilion (Larsen et al., 2012) ; c) variable extrusion shapes resulting from robotic slip casting processes (Lloret Kristensen et al., 2013).

Complex 3D geometries of different scales and degrees of complexity can be found, with large-scale smooth and curved surfaces being achieved mainly through the use of indirect, subtractive and formative digital fabrication processes for formwork production such as 3D milling, 2D Cutting and formwork tables for panelling systems. Such forms expand on the traditional

language of smooth concrete surfaces as seen in the classic examples of chapter 2, mainly in the increase of geometrical precision and the degree of curvature variability without the need for geometric rationalisation. A more clear point of departure in this topic is the new possibility of creating highly complex and detailed geometries with very small resolutions.

A case that directly relates to this emergence of highly differentiated forms is the use of topology optimisation as a design strategy in the production of load bearing structures. Topology optimisation uses computational simulation processes to design structurally efficient construction elements, by minimising material usage (and weight) where not necessary, according to existing forces. This and other optimization processes can result in complex branching structures that are now feasible through the use of direct and indirect additive processes with high detail resolutions, such as 3D milling and 3D printing of moulds.

On the other hand, the transition from standardised modular components to variable modular components is a natural consequence of using digital fabrication technologies in prefabrication settings. While past precast solutions depended on the use of standardised geometries and repetitive forms (for instance in the case of the prefabricated structural elements developed by Miguel Fisac or Nervi), digitally enhanced concrete prefabrication strategies move past this limitation, allowing for the creation of variability within prefabrication conditions. Nevertheless, considering that specific digital processes still present specific constraints such as dimensions and curvatures, modular yet geometrically variable design languages are of particular relevance in the context of concrete digital fabrication.

Finally, some of the studied examples reveal a re-emerging formal theme in concrete digital architecture that can be defined as digital process specific formal vocabularies. Specifically, designs with geometric features that are intrinsically linked to the particular digital fabrication process used, allowing for the creation of a new design vocabulary. Cases such as the ruled surfaces of Robotic Hot Wire Cutting and the extrusion volumes of some 3d printing systems or the deformed shapes of textile formwork moulding systems are examples of possible geometrical subsets directly resulting from digital fabrication processes.

As is patent in some of the cases, it is the development of the digital fabrication strategy and its resulting specific formal vocabulary that leads to the design solutions, strengthening the tectonic relations between form and process for digital fabrication. This is opposite to a more traditional case where fabrication processes are chosen to suit a specific design intent. Nevertheless, there are examples of similar, more limited examples of this logic in traditional cases, for instance, the panelling systems developed by Miguel Fisac, using textile moulds or the formal

language of inflated shells derived from textile formwork. In these cases, relevant efforts where placed in the development and exploration of alternative casting and formwork strategies which led to new formal vocabularies. Although in many other cases, forms were merely constrained by construction processes, there is nevertheless a line of continuation of traditional tectonic logics already mentioned in (section 2.3) - Concrete in traditional architecture.

Expanded Surface

Regarding the issue of *surface*, continuous, smooth apparent surfaces have been a staple of concrete architecture in the past as was described in examples from chapter 2. Therefore, there is still an overall push to achieving the same qualities with digital fabrication processes as was found in several of the studied examples presented earlier. These are mostly related with the digital fabrication of precast components using formwork or in general as the most desired end quality of exposed concrete. Besides this, regarding the issue of surface, we find the same two recurring themes in the studied examples and processes: a) artificial surface textures and b) digital process-driven textures.



Figure 3.34: Surface in digitally fabricated concrete: a) artificial surface textures through post-processing (Clifford and McGee, 2018) and b) through formwork design (Villa Bio, Ruiz-Geli, 2008); c) digital process-driven surface textures through 3D printing layer deposition (Xu et al., 2020) and d)(Xtree, 2020).

This first aspect found in digital fabricated concrete works is the creation of artificial surface textures or small geometrical features that operate as textural effects and not as overall geometric shape definitions. This theme has direct relations with the category of post-processing surface effects with techniques such as bushhamering referred to in the previous chapter and exemplified in the works of I.M Pei and Paul Rudolph. Direct subtractive processes such as 3D milling of concrete elements have been shown to reproduce and potentially expand this language as was

demonstrated in the Cyclopean Cannibalism project (Figure 3.34 a)).

Moreover, in some of the studied cases, the increased level of geometrical detail that is possible with 3D Milling or 3D printing of formwork and with some direct 3D printing systems has enabled the creation of complex textural effects not necessarily linked to the process, the material or the overall form. In such cases, textural effects are not achieved through post processing, but using the capabilities of the digital fabrication processes at an earlier stage, either formwork making or in the casting or printing stage (Figure 3.34 b)). Only in the case of direct subtraction of concrete a more close relation with traditional bush-hammering techniques was found. Nevertheless, it can be argued that there is a similar artificial or atectonic relation with the concreting process in favour of more visual and haptic surface expressions.

Finally, one of the key aspects of concrete tectonics and one of the major sources of exploration in the language of concrete architecture found in traditional examples was the appearance of trace marks from the formwork and casting process. These were referred as casting traces and illustrated in chapter 2. These features are still relevant in the digital context and the language of these process driven surface textures has found new and expanded avenues of expression with digital fabrication. If before, surface textures were mainly casting traces, in this expanded context, digital process-driven surface textures can assume a multitude forms, being a consequence of the existence of new fabrication tools which create different impressions either directly on concrete or indirectly, through formwork.

In the case of formwork, such marks can be milling paths, wire cutting paths or 3d printing layers, in the subtractive or additive creation of mould shapes. In direct digital fabrication processes, 3D printing layers of various sizes and other small scale 3D printing textures are recurring traces in additively fabricated concrete structures (Figure 3.34 c)). These surface effects present new opportunities for interesting explorations of different languages and although some of these effects are direct and unavoidable consequences of a process, in some cases they have already been explored as aesthetic expressions. For instance, the Building Academy Extension by SOMA Architects, where CNC milling toolpaths were explored as surface textures in cast concrete, or in the woven textures of the 3D printed concrete benches by xTREE, which explore the layers of concrete extrusion as drivers for textural effects (Figure 3.34 d)). These works go beyond the direct expression of a process, to exemplify a clear expansion of the language of concrete through the exploration digital fabrication as a driver for design.

Expanded Composition

Finally, regarding the third issue of concrete tectonics, material *composition*, it is still relevant to refer to the same topics as mentioned in chapter 2 of this thesis: a) performative motivations and b) aesthetic motivations.



Figure 3.35: Composition in digitally fabricated concrete: a) performative composition effects through 3D printing of reinforcement materials and b) the variation of material density; c) aesthetic composition effects through 3D printing of variable color.

Considering performative motivations for controlling material properties in digital fabrication processes, in the studied cases there seems to exist a stronger effort to control material properties focusing on process performance than on architectural performance. A common denominator in the use of digital fabrication technologies in general is the relevance of the material composition for the overall viability of any fabrication strategy. This is usually a technical consideration with different responses for different processes. For instance, the detail and quality of direct 3D printed extruded concrete structures depends greatly on controlling material properties of concrete in its wet state. Properties such as rheology and workability are fundamental in order for the material to be extruded but also to retain its shape and bond with previous layers. In other indirect digital fabrication strategies using formwork, such as 3D printed moulds or 3D milled moulds, the geometrical complexity of the use cases dictates the necessity of using concrete mixes with increased plasticity, that can correctly flow and fill all interior cavities of the moulds. For the same reasons, non-traditional strategies for reinforcement are also necessary such as steel or plastic fibre reinforcement.

Nevertheless, some processes directly focus on integrating digital fabrication to enhancing particular components of the composition of concrete, such as 3D printed meshes that simultaneously work as lost formwork and as reinforcement material. These examples can be understood as expansions of past experiments such as Nervi's ferrocement, by enabling thin curved geome-

tries, while maintaining adequate material resistance (Figure 3.35 a)).

Another re-emerging area of research that connects material composition and digital fabrication is the use of heterogeneous material compositions. While traditionally, concrete is cast with homogenous compositions, and many digital fabrication processes follow this trend, the use of some processes such as multi-material 3D printing are recovering the use variable compositions in concrete architectural elements. This can have potential effects both on architectural performance and on aesthetic expression.

On one hand, such processes hint at the possibility of creating optimized structures through the use of material density or porosity gradations (Herrmann and Sobek, 2017). While this idea of variable material compositions was already present with functional purposes in works such as the Roman Pantheon, its use can be expanded in conjunction with 3D printing processes, in the creation of concrete structural elements with varying strengths, weights and other properties such as thermal insulation, in continuous gradations (Figure 3.35 b)).

On another hand, some of the studied examples, use the logic of heterogenous material compositions not for funcional purposes, but with aesthetic effects, when applied to the variation of other material properties. Visual properties that stem directly from material composition, such as color, have been historically used in expressive concrete works, already mentioned in chapter 2. As demonstrated by the 3D printing examples in (subsubsection 3.1.2.3) - Concrete Extrusion, which use varying pigment densities to achieve color gradients, digital fabrication can also operate on this front, opening new aesthetic and design possibilities related to this aspect of concrete tectonics (Figure 3.35 c)) .

3.3 Critical issues for digital fabrication

To this point, we have show the possibility for digital fabrication strategies to continue and expand traditional concepts of form, surface and composition. It has also been made clear that each digital fabrication strategy is characterised by a combination of strengths and weaknesses in key aspects regarding the creation of concrete architecture. From all the previous analysis developed earlier, we conclude that in a general sense, digital fabrication technologies for concrete have great potential, both technical and tectonic but also present a set of critical issues that should be addressed to further their implementation into practice.

The first major issue concerns the question of form in relation with process efficiency and sus-

tainability. More specifically, the balancing of geometric freedom, with production and material optimization both as economic and sustainability concerns. As presented in Figure 3.31, several analysed digital fabrication strategies present the ability to create virtually any geometrical form. Nevertheless, to achieve such features, much of these processes present either high production times or high material waste production. As an example, this issue is particularly relevant in the case of CNC milling of EPS moulds. Being still one of the most used digital fabrication solutions for concrete architecture today it is an important comparison point. Although CNC milling is widely used and a useful process for the production of complex and customized formwork solutions, it is also limited when considering three key aspects. First, high production times resulting from the high-resolution milling process necessary for smooth finishes. Second, low efficiency in material optimization, considering the large quantities of material discarded as waste for each mould surface produced through milling, when compared with the potential absence of waste from other subtractive or additive processes. Finally, both previous issues contribute to high overall production costs, from materials, labor and fabrication times.

Therefore, CNC milling of EPS moulds is usually considered a cost-ineffective process only suitable in works of exceptional character and budgets, with particularly complex geometries. This issue was apparent in the recent case of the Waal Bridge Extension by Zwart Jansma (Figure 3.8). The curved geometry of the bridge was realized using traditional, manually produced wood formwork despite its freeform geometry, after considering the high costs that CNC milled moulds for such an extension would entail (Søndergaard et al., 2016).

A comparable argument can be made when considering most 3D printing techniques for concrete. Although a multitude of these additive methods have the capacity to fabricate highly intricate shapes, as previously noted, this increased design flexibility generally entails an increase in both production times and costs. When this is not the case, for instance in concrete extrusion, the reverse is true, sacrificing speed for geometrical freedom.

So, the other side of this balancing issue is that other relevant digital fabrication processes, while possibly more optimized, are frequently limited in possible geometries, hindering their adoption outside of the academic realm. Processes such as formwork moulding or slipforming have increased efficiency and sustainability through the use of adaptable moulding strategies, but result in very specific formal architectural lexicons that although interesting in regard to their design potential, limit their general usability.

The second relevant issue is the adaptability and integration of digital processes into the construction industry, as analysed in the last column of Figure 3.31. Indirect and direct additive

processes such as 3D printed formwork and 3D printed concrete present substantial improvements in sustainability by theoretically eliminating waste production from formwork subtraction or from through bypassing its need. Although potentially disruptive, these processes also require highly technological setups and multidisciplinary knowledge. Moreover, while some experiences have been developed using mobile robots and large-scale building site gantries, most existing processes are more suited to the controlled environments of prefabrication plants and laboratory settings. Their application in the construction industry is therefore not yet easily fulfilled in current industrial contexts, requiring the transformation of existing processes, methodologies and equipment, presently limiting the possibility for their adoption and widespread use.

Considering the issues presented here, we posit that it is still relevant to explore other digital fabrication processes that can potentially expand the formal and expressive possibilities of concrete architecture, while simultaneously balancing the issues of sustainability and ease of integration.

Although currently there has been a shift away from subtractive processes and there has been a substancial emergence of potentially disruptive additive 3D concrete printing processes, we believe that a subtractive process such as Robotic Hot Wire Cutting (RHWC) can still be a relevant alternative.

First and foremost, RHWC deals with the main consideration of increasing available formal freedom, while simultaneously increasing fabrication speeds, leading to decreased construction times and costs. Second, its slicing logic also presents relevant opportunities for increasing material efficiency in formwork production when compared with other subtractive processes. Third, as a solution for formwork production, its integration in the construction industry is not disruptive as it doesn't imply profound changes of current construction systems and processes. Fourth, RHWC is an adaptable process for different design solutions, being applicable both for in-situ construction and concrete precasting, following an increasing design trend for the prefabrication of lightweight construction systems which can also present sustainability benefits when compared with monolithic construction.

RHWC also benefits from advantages similar to other indirect subtractive processes for casting concrete. Casting subtracted moulds tends to be more precise at larger scales, when compared with 3D Concrete Printing, particularly extrusion methods and the resulting exposed finishing qualities are smoother than most 3D printing processes. Also, in terms of material performance, cast concrete is generally mechanically stronger than current 3D printed concrete for similar mixes (Rahul et al., 2019). Moreover, it does not require specific concrete materials science nor imposes specific concrete mixes for its use, fully benefitting from any advancements in

this regard, while 3D concrete printing mixes require careful considerations (e.g. aggregate size, reinforcement, rheology) in order to be used as such.

In conclusion, we find that 3D cutting processes and particularly Robotic Hot Wire Cutting (RHWC) can be presented as a viable and tectonically relevant digital fabrication technology for concrete architecture.

Chapter 4

Material explorations

This chapter focuses on the experimental development of a specific technology, Robotic Hot Wire Cutting (RHWC), as a demonstration of the possible contribution of digital fabrication to the problems raised.

It is divided into five subsections. An introductory section, followed by the description of four experimental prototypes (Figure 4.1): *3D milling vs RHWC*, *The MSE Panels*, *Revisiting the Philips Pavilion*; and *The Corkcrete Arch*.

The first prototype, establishes a baseline comparison between 3D milling and RHWC and characterises the main procedural advantages of RHWC.

The second prototype presents the initial developments of a mould design strategy for RHWC fabrication (layered moulds) and explores the concepts of form (prefabrication of variable elements and complex geometry), surface (textural vocabularies) and composition (material layering) in this process.

The third prototype further develops the layered mould fabrication strategy on a real case-study - le Corbusier's and Iannis Xennaquis' 1958 Philips Pavilion - focusing on improving the material sustainability of RHWC of EPS moulds and also analysing the design implication of such processes.

The fourth and final prototype attests the feasibility and applicability of the strategies and processes developed in the previous experiences, in an industrial setting, in the construction of a complete self-sustaining arch structure, composed of lightweight modular prefabricated elements, with a complex ruled geometry.

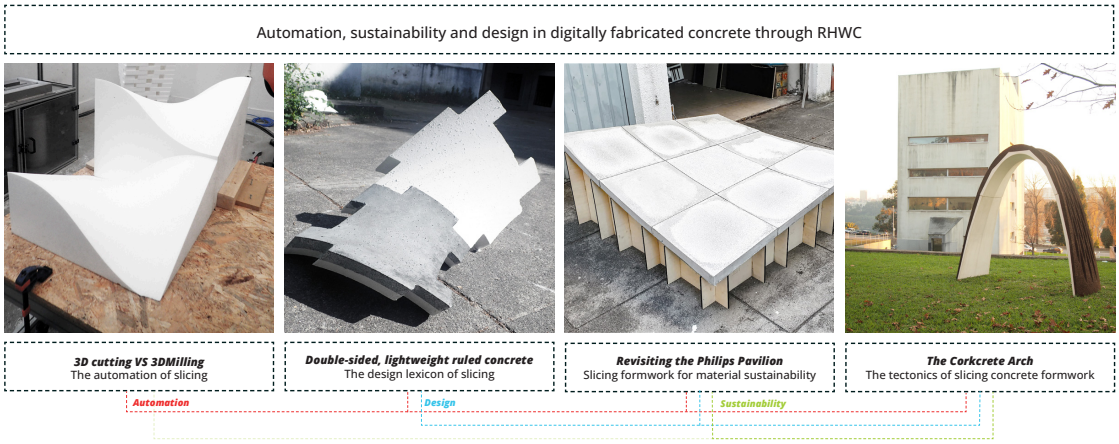


Figure 4.1: Experimental works developed in the scope of this dissertation.

4.1 Base Concepts of Robotic Hot Wire Cutting

In this section, the principal concepts surrounding robotic hot wire cutting are presented, starting from a general characterization of the main geometrical features of its application, the general methodological steps for programming the robotic movements for RHWC, the description of the actual experimental setup and base materials used throughout all experimental prototypes.

4.1.1 The geometry of RHWC

One of the main features of robotic hot wire cutting in the production of concrete formwork, is the use of a 3D cutting logic, i.e. *slicing*, which corresponds to the robot-assisted movement of a cutting tool. When this tool is a linear wire, this spatial line movement defines a particular subset of 3D geometries, resulting in the main design feature of RHWC: the production of ruled surfaces.

Many known particular ruled surfaces exist, from simpler ones such as the plane, the cylinder and the cone (both single curved, developable surfaces), to more complex ones such as the hyperboloid, the conoid, the hyperbolic paraboloid and the helicoid (double-curved, non-developable surfaces) as well as other general single and double curved surfaces.

Ruled surfaces can be used to create elegant curved shapes which have been featured extensively in concrete architecture, particularly in the second half of the XXth century (subsection 2.3.1). Examples of self-supporting hypar thin shells, conoid roofs, helicoidal concrete stairs, as well as hyperboloid concrete towers are common (Figure 4.2). Not only are these curved surfaces more easily described and understood by their geometrical features (when comparing them with general free-form surfaces), they also represented a cost-efficient way of creating curved surfaces by using linear elements such as wood beams, taking advantage of the presence of their embedded straight line segments to create formwork for casting.

Ruled surfaces can also be useful as a rationalization strategy for general freeform surfaces. In mathematics, ruled surfaces have zero or negative gaussian curvature throughout, meaning that spherical-like ruled surfaces do not exist, and such curved surfaces with positive gaussian curvature are impossible to build from ruled surfaces without approximating them with assemblies of trimmed surfaces. Nevertheless, in these cases, ruled surfaces can still be used to rationalise or approximate more complex, positively curved freeforms through trimmed strips of ruled sur-

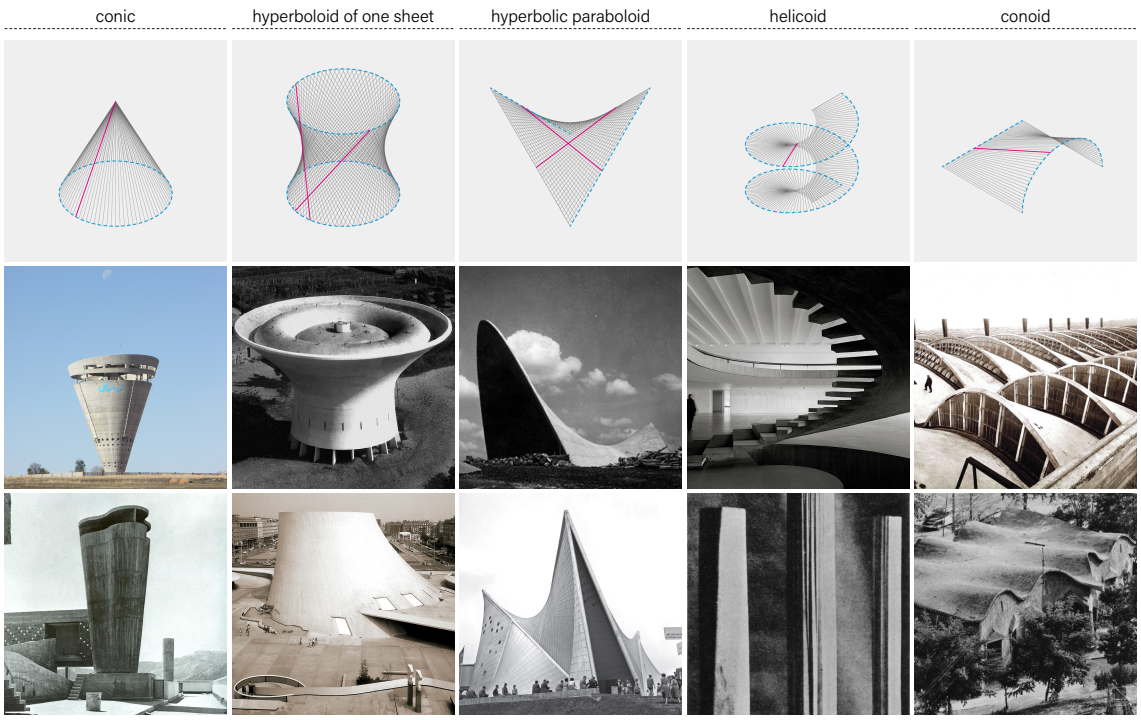


Figure 4.2: Basic types of ruled surfaces and examples in traditional architecture.

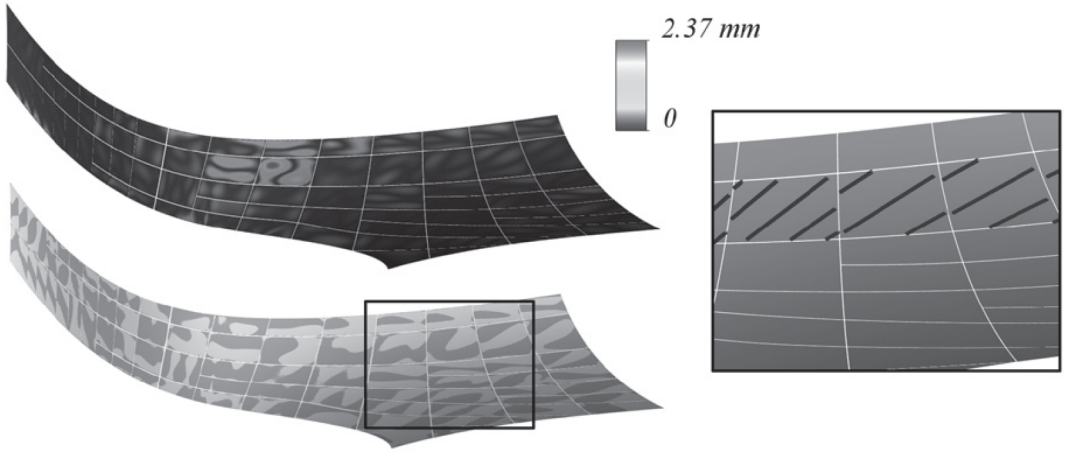


Figure 4.3: Facade detail of Soho Galaxy by Zaha Hadid Architects, illustrating the application of ruled surface approximation for general freeform surfaces. Detail on the right, showing the distinct direction of the ruled generatrices in each panel geometry. Note the lack of continuity between panels, denoting the rationalization of the general curvature (Flöry and Pottmann, 2010).

faces (Flöry and Pottmann, 2010) (Bartoň et al., 2014). This allows for the description of such complex freeform surfaces, at reduced costs (when compared with freeform digital fabrication processes such as milling) without rationalization into more simple geometries such as planar, spherical or cylindrical surfaces Figure 4.3.

Another relevant geometrical feature of ruled surfaces for architectural applications is their direct relation with developable surfaces or surfaces which can be planarized without distortion. Developable surfaces (also called single curved surfaces, in opposition with double curved surfaces which are non-developable) have o gaussian curvature meaning that while not all ruled surfaces are developable (e.g. the double curved hyperbolic paraboloid), all developable surfaces are ruled surfaces. As such, any process able to create ruled surfaces will in theory also be able to create any developable surface. For architectural applications this means that RHWC would also be a geometrically feasible process for use with any bendable sheet-like material.

In Elementary Differential Geometry (O'neill, 2006) a ruled surface (also referred as a scroll surface), is defined as *a surface swept out by a straight line L, moving along a curve b* (Figure 4.4 a)). Accordingly, any surface is ruled if through all of its points, at least one straight segment can be found that lies on the surface. These positions of L or straight segments of the ruled surface are called **generatrixes** or rulings and a curve in that surface that intersects all such generatrixes is called a **directrix** or director curve (Krivoshapko and Ivanov, 2015).

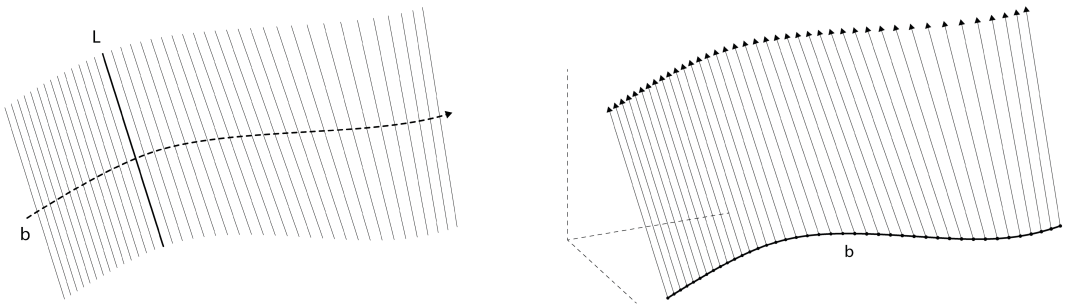


Figure 4.4: Ruled surface definitions: a) Ruled surface as a straight line (L), moving through space along a curve (b); b) Ruled surface as a line L and a vector field, defining the directions of L at each point on the base curve b.

O'Neill describes the parametrisation of a ruled surface as $x(u, v) = b(u) + vd(u)$, where b is the base curve through which the line L moves and d is a second directrix curve which intersects all generatrix lines, mentioning that d can also be understood as a vector field on b pointing

along the line L (Figure 4.4 b)). These different descriptions of ruled surfaces also translate into geometric generation methodologies in computational design tools.

In most 3D modelling softwares, a ruled surface can be described by a combination of the three mentioned elements, by sweeping a generatrix line placed in a specific position (g) along two directrix curves (Figure 4.5) (d1, d2). This methodology is usually useful for design purposes, as it begins with the creation of 3 or 4 "boundary" curves that define an interior area which can translate to a design element such as space enclosure (i.e. a wall). Therefore, one or two opposing lines (both generatrixes) and two opposing curves or lines (directrixes) become the driving inputs of such surfaces and the precise control of these boundary shapes becomes the subject of the design. Many times these geometrical inputs of ruled surfaces are apparent in the finished architectural elements (Figure 4.2) giving them an increased awareness of this intrinsic design logic.

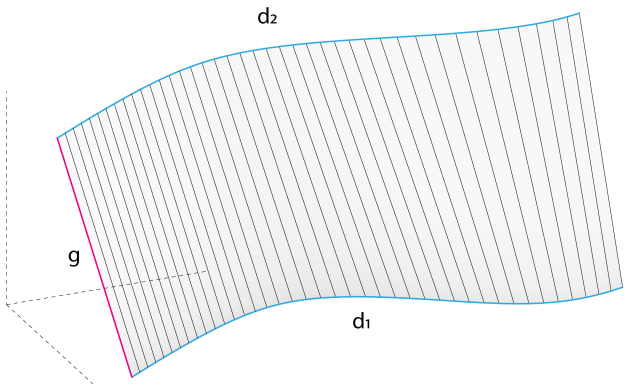


Figure 4.5: Geometry of a general ruled surface created by sweeping the generatrix g through space, following two directrix curves d1 and d2, modelled in Rhinoceros 3D.

The second description for the generation of a ruled surface (Figure 4.4 b)) which removes the second directrix, by sweeping L along a base curve, using a set of orienting vectors for L directions (Figure 4.7 a)) is also relevant in the context of robotic programming. While harder to visualize, using non-parametric 3D modelling softwares, it can be considered a useful description of a ruled surface for RHWC purposes: a set of vectors, along a curve in space. Moreover it is, in a sense, a more complete definition to understand in this case, because it relies in the definition of all the generatrix directions in the desired surface and not merely the combination of one generatrix and directrices.

Although as mentioned above, the architectural design of ruled surfaces is more practical using a combination of generatrix and directrix "boundary" curves, any such combination can be parametrised in different ways. This can result in slightly different surfaces. A simple example can be pictured by imagining the ends of an elastic line following 2 directrix curves where the rate at which both ends of the line follow these curves can be different, thus resulting in different ruled surfaces. Therefore, when transitioning from a pre established design geometry into fabrication it is often important to find the actual rulings of a surface and not just recreate them from directrix and generatrix "boundary curves" which can result in missmatches between design surfaces and fabricated surfaces (Figure 4.6).

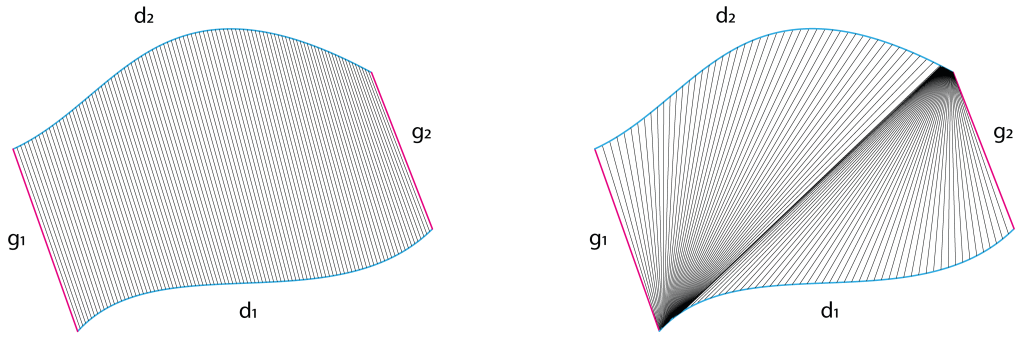


Figure 4.6: Example of two different ruled surfaces generated from the same set of boundary curves.

While in the definition above, the orienting vectors were considered with origins in a base curve and thus at an end-point of the generatrix, for RHWC it is more useful to consider them in the center of the generatrix (Figure 4.7 b)). Because in practice, the generatrix line is actually a fixed segment (the wire) it becomes relevant to establish its position sideways. Also, in a robotic setup, calibration of tool positions is done through a tool center point which can be more easily translated by projecting the center of the last axis to the wire, in the local z direction (approximately in the center of the wire).

With these aspects in consideration we can thus translate the main geometrical features of ruled surfaces into the realm of RHWC:

- a **generatrix** or ruling line corresponds to a position of the cutting hot wire
- a **directrix** is the path that a point in the wire travels in space (e.g. an endpoint or center of the wire)
- orienting vectors are positioned in the generatrixes and point in the direction of the hot wire.

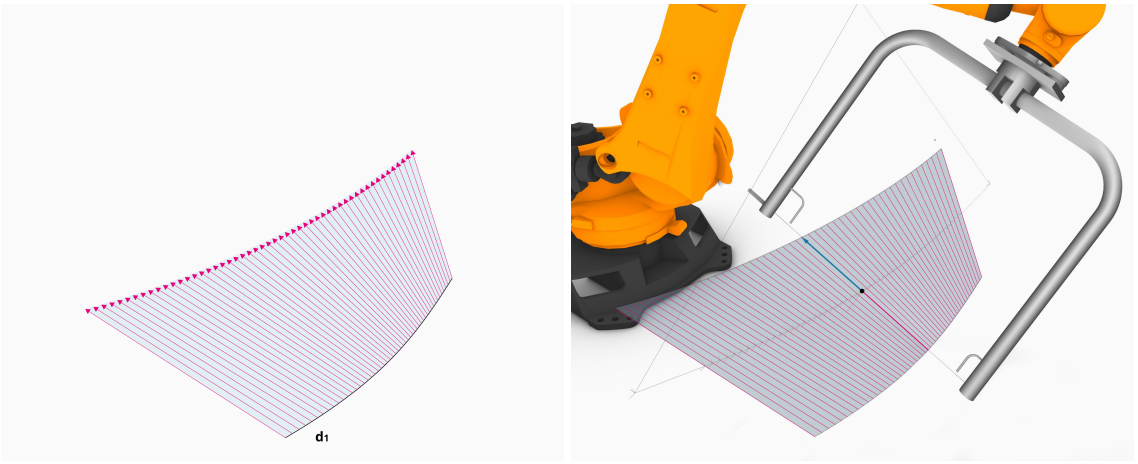


Figure 4.7: Ruled surfaces through vectors: a) General description using a base curve (d1) and a set of orienting vectors; b) the same surface, swept by a RHWC setup, noting the wire in the direction of a ruling line and the vector origin in its center. The grey line is the path that the center of the wire travels through space.

With these geometrical features, one can describe any ruled cutting surface which travels through space, intersecting a block of EPS foam or another suitable material, creating a cut section.

In this cutting process, several versions of a ruled surface can be relevant to consider: the originally 3D modelled surface, the part of the surface actually described by the wire segment, the surfaces in the material resulting from the cut and the desired surface in a finished cast concrete component.

All these surface patches are partially coincident and we can define the three more relevant ones (Figure 4.8):

- The *Cutting Surface* (CS) which represents the main defined surface path of the wire in space, through the stock material, excluding other variables such as entry and exit offsets.
- The *Material surface (MS)*, which is the actual result of one cutting operation on a stock material block.

- The *Design surface (DS)* which is the desired surface geometry for a specific cast component.

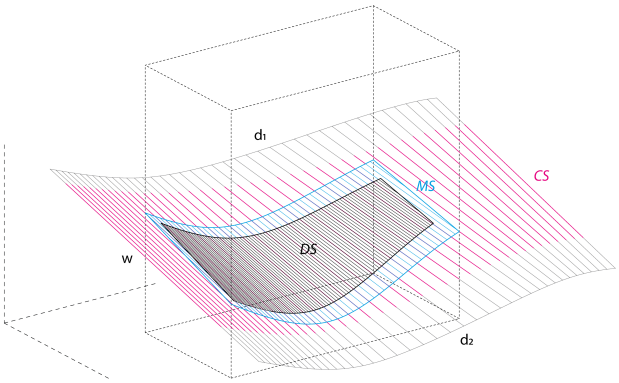


Figure 4.8: Relevant surface patches for an imaginary concrete panel geometry, inside a stock block. DS - design surface, or the actual desired component geometry; MS - material surface, or the actual fabrication result from one cutting pass; CS - cutting surface, the full surface path that the wire takes in a cutting pass.

Although possible, the design surface (DS) is not necessarily the same as the cutting surface (CS) or the final fabricated material surface (MS). These will all be coincident surface patches but can have different sizes or extensions in the generatrix direction or in the directrix direction. Particularly if the design geometry requires a perimeter shape different than the intersection between the stock volume and a cutting surface.

As a general methodology, one can extract the design surface for fabrication directly from the design 3D geometry, and the cutting surface can be an extended version of the same surface to account for the stock and wire dimensions. The corresponding material surface will always be the intersection between the stock volume and the cutting surface.

Material surface and design surface can be equal in many situations. For instance, if the design surface can be reoriented inside the stock volume to force this position; if the stock material is cut to that exact shape before any other cutting operation or in the case of a subdivision of a continuous design surface into smaller parts, if the subdivision shape takes into consideration a predetermined stock volume shape. The advantage of such cases is that when DS=MS the perimeter geometry of any resulting element is defined at the boundary of the stock material and there is no need for other cuts or perimeter shaping methods.

For these reasons, the issue of boundaries and perimeters is very relevant when working with RHWC, particularly when creating moulds for precast concrete elements, which require a closed boundary for casting.

While within the constrains already mentioned, the concept of describing ruled surfaces of arbitrary shape is generally true for RHWC, other practical issues can impose further geometrical limitations. Some of these were experimentally explored and will be described further in subsection 4.2.5 - Practical issues of RHWC.

4.1.2 An algorithm for robotic hot wire control

From the design, to a finished fabricated concrete element, several steps are necessary. These include the design of the intended geometry, its subdivision (if necessary), the design of the required formwork parts, robotic programming and fabrication, formwork preparation, concrete casting and finally demoulding.

In this multi-stage process, robotic programming is necessary to define the cutting paths of the robotic arm, to successfully achieve the desired design geometry (or mould geometry in the case of RHWC for casting concrete). To define a cutting path for RHWC, from any designed surface it is necessary to correctly align and orient the hot wire end-effector through a series of positions in the ruled surface.

These positions of the hot wire will necessarily be coincident with the ruling lines of the surface geometry and although the actual surface could be described by vectors alone, as mentioned in the previous section, the specific case of using a robotic arm to describe such surfaces implies that not only the wire must be in the correct position, its rotation along itself must also be defined as that has relevant implications in the position of the robotic arm. Thus, each tool position and orientation can be fully defined in space as a cartesian frame composed of a set of x,y,z cartesian axes with an origin point (Figure 4.9).

The full movement of the robot for one or more cutting paths is therefore a series of such frames, with added information regarding movement type, speed, entrance and exit offsets, which are used by the Kuka|PRC core component to calculate the inverse kinematics[1] for the specific robot model and produce the code which is actually read by the Kuka robot controller (KRL).

[1] Inverse kinematics is the mathmatical process to calculate a set of joint parameters (rotations), necessary for a robot to achieve a certain predefined position or group of positions.

To define all the positions for a hot wire cutting path in a surface, an algorithm can be generalised by following a series of simple steps:

1. Extract a series of equidistant generatrix lines of the design surface.
2. For each line, define a 3D frame aligned to the respective generatrix using:
   a) A point, **A**, in the generatrix line to establish the wire center point;
   b) A second point, **B**, in the generatrix line (usually an end point) to define a direction for the wire;
   c) A third outside point, **C**, to orient the end effector around the wire.
3. Define the type of movement to be followed between all frames (LIN; PTP; SPL[2])

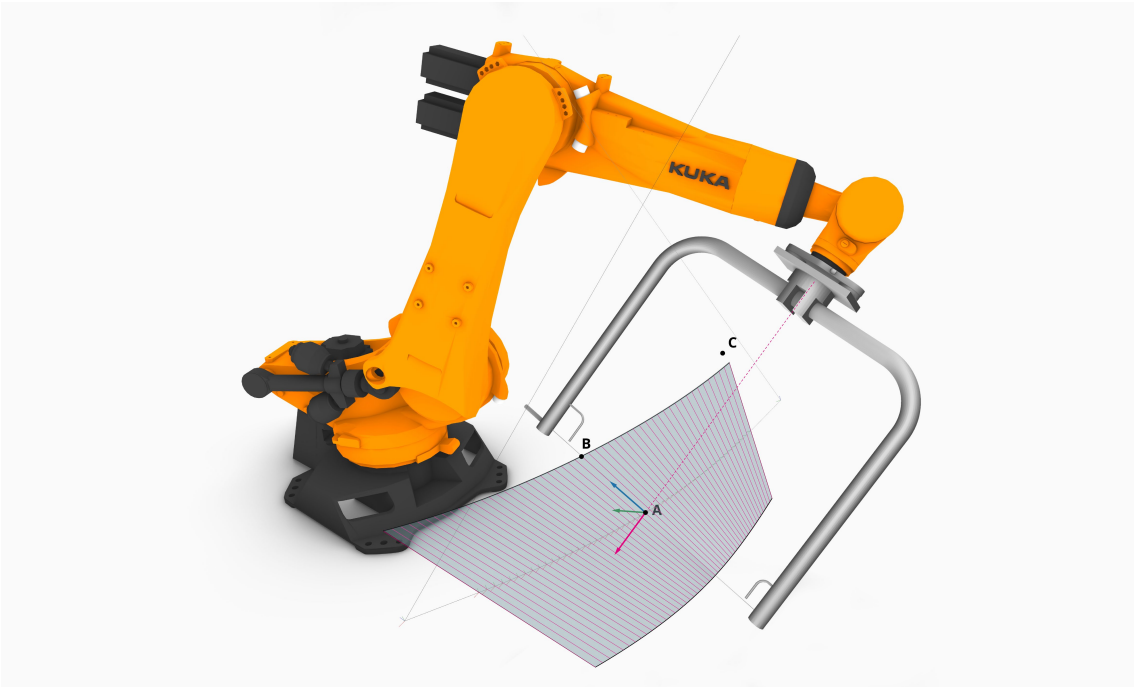


Figure 4.9: RHWC tool position frame, constructed from three points.

The number of generatrices used to create the robot movement will define the precision of the cutting wire describing the surface geometry, as well as interpolation parameters within the

[2] Linear movements (LIN) are those where the tool center moves from one point to the next in a straight line; In Point-to-Point (PTP) movements, the robot tool center moves from one point to the next using the shortest path according to the rotation of the axis

Kuka|PRC main component which control the smoothing of the robot movement between the defined positions. Smoothing parameters are relevant, because any jerking movement or small stops between points will generate visible cutting patterns in the EPS surface.

The center of the hot wire and origin of the frame (A) is usually defined as the mid point of the generatrix lines, in order to maximize the cutting length of the wire and avoid collisions of the end effector with the stock material. The second point (B) along the generatrix will define the direction of the wire, which is coincident with the segment [AB] but can point in either direction of that line possibly causing a 180º rotation in the robotic arm.

The orientation point (C), can be the same for all tool positions or can vary along the path and the three points A, B and C define the plane where the end-effector (the U-shaped frame) lies. The position of these orientation points (C) has no consequence on the actual surface described by the wire, but is critical for the actual positions of the the end-effector structure and the robot arm. Its control is fundamental to avoid collisions of the RHWC end-effector with the stock, with the robot body or to avoid creating unreachable points along the surface.

Figure 4.10 a),b),c) illustrates, respectively, differences in robot positions for the same wire position with different orienting points (C1, C2), a cutting path with only one orienting point for all tool positions and another with one for each, both describing the same surface.

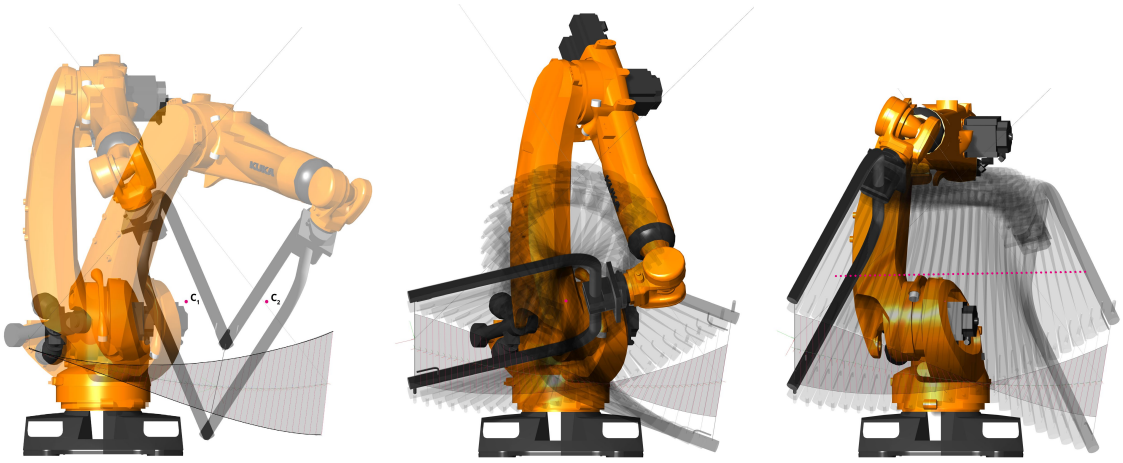


Figure 4.10: Controlling the movement of the robot, using orientation points: a) variations in robot position for same wire position; b) full cutting path with one central orienting point; c) full cutting path (same surface) with several orienting points.

Besides the previously defined positions along a cutting surface, the full movement of the hot wire also incorporates other positions outside of the cutting surface that allow for better control and transitions of the robot while entering and exiting the stock material. Thus, in terms of all

the movement steps involved, a full cutting path for RHWC consists of:

1. Starting Position. A position where the robot moves to at the beginning of the routine, having some influence on the general reach of the robot.
2. Starting offset. An offset position (or series of positions) added immediately before the first tool point in the defined cutting surface, used to guide the approach of the tool to the material. It is usually tangent to the surface or offset in a cartesian direction.
3. Hot Wire Tool paths. The actual set of positions that define the main part of the cutting surface, related to the desired design surface.
4. End offset. A position (or series of positions) added after the final tool point in the cutting surface, used to ensure a correct exit of the tool from the stock material.
5. End Position. The final position of the RHWC tool where the usual concern is to remove the robot from the working area without colliding with it or the cut pieces.

Using this simple algorithm and arrangement of positions, many such paths can be defined and chained together to create a more complex cutting routine (Figure 4.11).

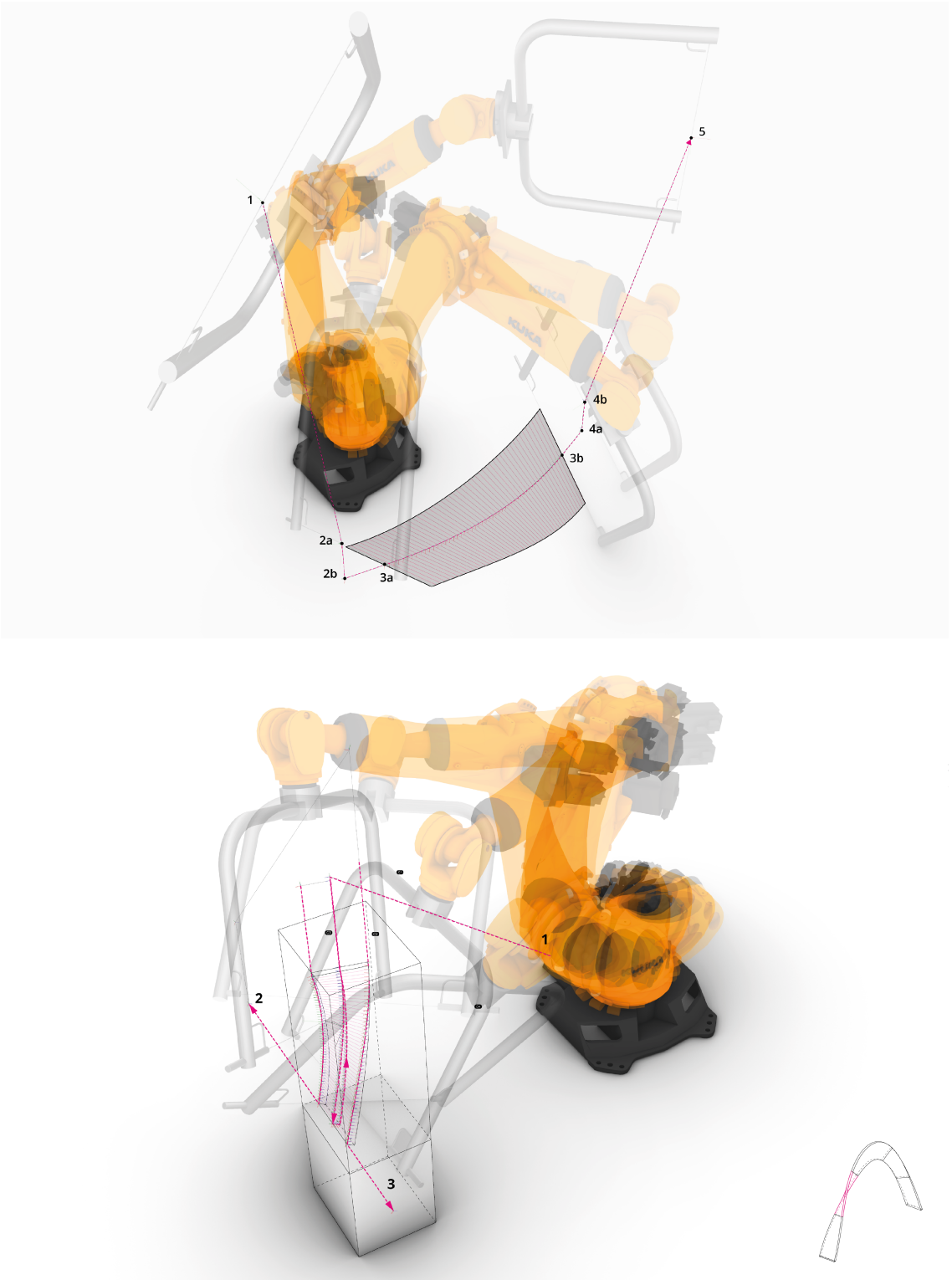


Figure 4.11: RHWC cutting simulations: a) one full cutting path with added start and end positions (1,5), start and end offsets (2a, 2b, 4a, 4b), for one surface; b) chaining three cutting paths for cutting several surfaces (1-front and back sides, 2-left side, 3-right side).

4.1.3 The RHWC setup

As referenced before, in (subsubsection 3.1.1.1) - 3D Cutting, RHWC is a particular application of what we defined as 3D cutting. An indirect subtractive digital fabrication strategy, mainly used to produce complex formwork elements for concrete construction, using polystyrene foam blocks or other materials with low melting points, through slicing. To achieve this, a robotic fabrication cell is used, composed of three main elements: a) an industrial robot; b) a hot wire end-effector; c) a power supply (Figure 4.12).

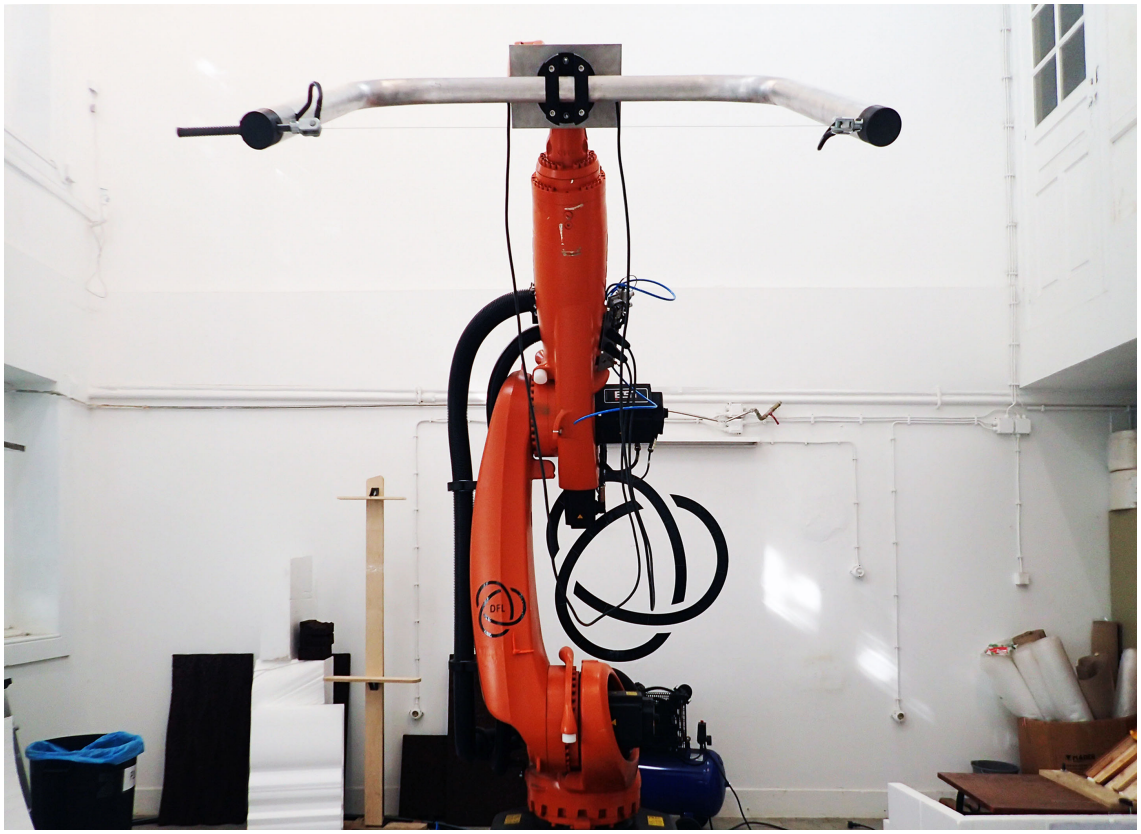


Figure 4.12: The Robotic Hot Wire Cutting (RHWC) setup at the DFL: 6-axis robot and hot wire end-effector.

For the experiments presented in this dissertation, the robotic system used was a Kuka KR 120 HA R2700. A high accuracy 6-axis robot arm, with a large working envelope featuring a maximum reach of 2696mm and a payload maximum of 120kg (Figure 4.13). The large envelope and precision is fundamental to work with full-scale construction elements. The full range of movement afforded by the available 6-axis of rotation of robotic systems and its large reach are also particularly relevant for RHWC, considering that the large dimensions of the hot wire end-effector represent added constrains to the overall maneuverability of the robotic cell and directly affect its ability to fabricate ruled geometries of increased complexity.

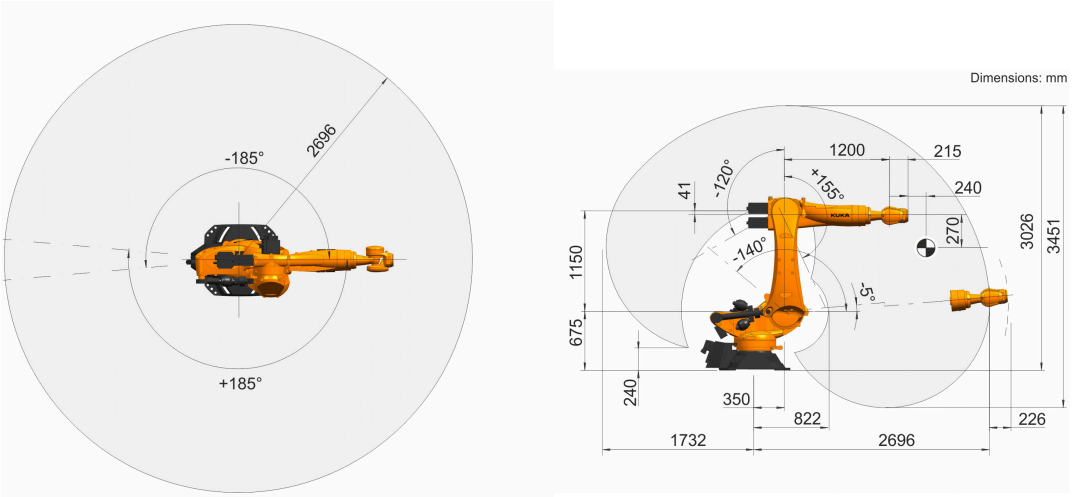


Figure 4.13: Kuka KR 120 HA R2700 6-axis robot. Dimensions and movement range.

The end-effector (RHWC tool) was developed specifically for this work. It consisted of a frame with an attached cutting wire, connected to a power supply. The frame consisted of a 60mm tubular, U-shaped aluminium structure, fitted with springs which tensioned a 0.25mm diameter NiChrome wire. A 3D milled custom part clamped the tubular structure at the center to a steel base with quick swap connectors to the robot head. The overall dimensions of the RHWC tool were 1077 mm of depth by 1220 mm of width, with an actual available cutting width of 854mm. These dimensions were defined to maximize the available working space while minimize any vibrations that would transfer to the cutting wire. The cutting wire was connected to an independent 230V-40V, 3A power supply, with a variable power switch to control the resulting wire temperature. The dimensions and relevant points are presented in Figure 4.14.

The practical functioning of the RHWC setup, as well as any hot wire system, is simple. The wire in the end-effector is composed of Nichrome (NiCr), a a high resistance alloy, able to withstand temperatures up to 1400º C. As the current passes from the power supply, through the

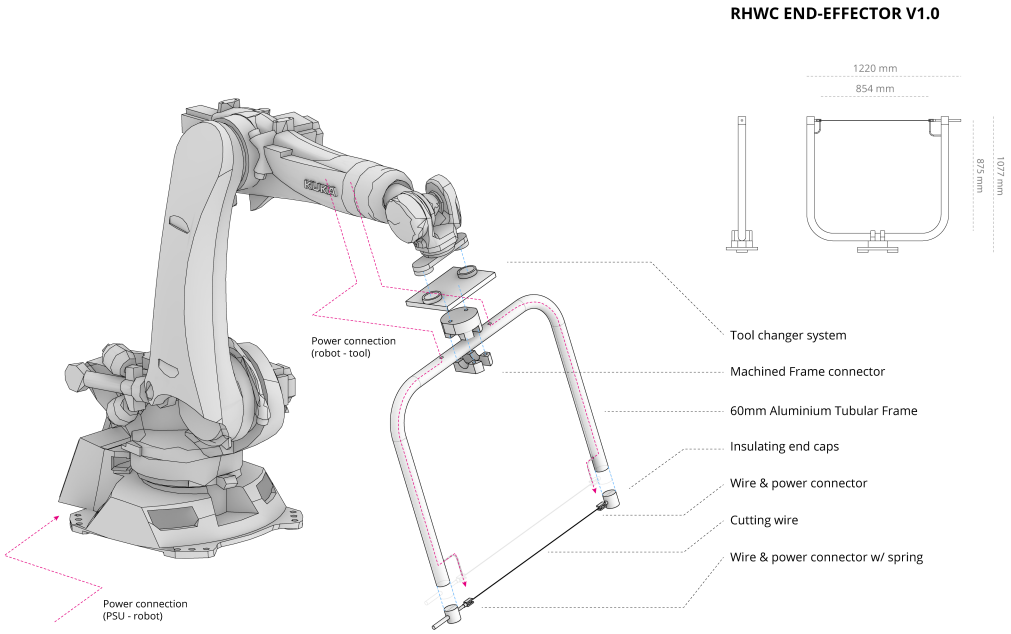


Figure 4.14: RHWC end effector detail and dimensions.

wire, the resistance that the wire imposes results in its heating, reaching up to 200º to 400º C. This temperature, combined with the moving speed of the wire through space is enough to instantly melt a stock material, with the wire passing through, effectively cutting, assuming it has a low fusion point such as the expanded polystyrene that is usually used for RHWC.

4.1.4 Formwork materials for RHWC

In the experimental work described in this chapter, although other materials were explored, the main material used as mould for concrete casting, in conjunction with robotic hot wire cutting was expanded polystyrene (EPS) foam blocks.

EPS was developed industrially in the 1950-60s, and the process of its manufacture consists in the introduction of a foaming agent and other additives to styrene, producing expanded beads of the material. These are subsequently formed, using moulds, pressure and heat, resulting in large blocks composed of the fused EPS beads, which are then commonly subdivided, in sheet forms, but also available in variable sized paralelipipedic volumes (Figure 4.15).

The low density cellular configuration that characterizes this material, in addition to endowing it with its known thermal properties, makes it suitable for the production of concrete moulds mainly through subtractive processes. Despite its reduced density, it has sufficient compressive



Figure 4.15: Expanded polystyrene blocks of large dimensions.

strength to withstand the forces generated by the casting process without incurring relevant deformations if braced correctly. For the same reasons, it is easily cut or milled with the necessary precision to correctly describe complex geometries.

It is interesting to note that practically since the industrial development of this material, applications related to the construction of concrete elements with curved geometries have emerged. The process called "Spiral Generation" (Figure 4.16) was developed and patented by DOW Chemical in 1966 as a solution for the construction of spherical concrete domes (Melaragno, 1991).

For the specific case of robotic hot wire cutting, EPS foam is also functionally ideal. This is because not only it has a very low density, but it also has a relatively low melting point which allows for the characteristically fast cutting speeds of RHWC through heat.

Preliminary experiments were conducted, using EPS and also extruded polystyrene (XPS) with manual hot wire cutting for the production of small moulds (Figure 4.17). Tests were conducted using two different wires, 1 mm and a 0.25 mm diameter nichrome wire, to test for any improvements in cutting time. Although hot wire cutting of XPS forms resulted in considerably smoother surfaces, it presented two major issues. First, the cutting process was much slower because of the higher density of this material. While EPS density is on average 23-27 kg/m3, with

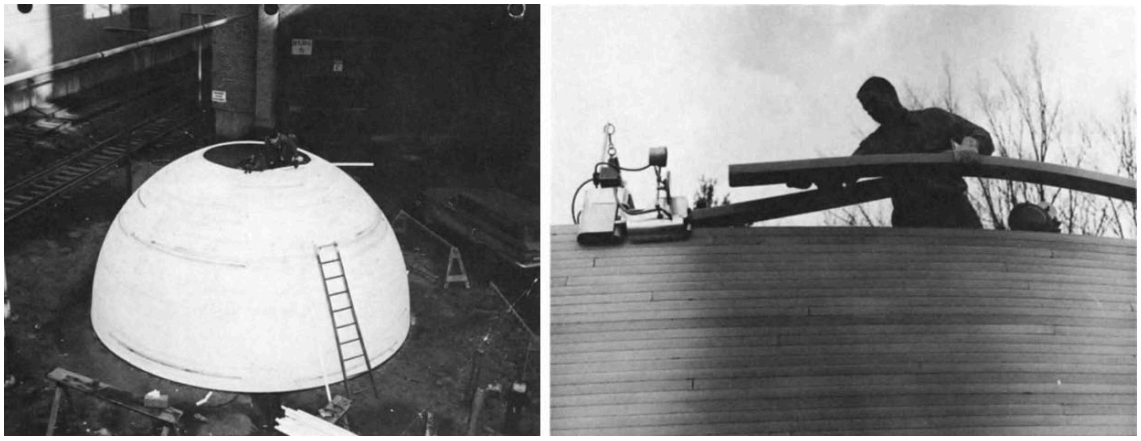


Figure 4.16: "Spiral Generation": early EPS formwork systems for curved concrete geometries

a melting point of about 100ºC, XPS density can reach 50kg/m3. Second, the readily available XPS formats were no thicker than 15-20 centimetres, which conditioned the possible curvature radius of any complex form to be cut, as any shape would have to fit in the available thickness. Stacking XPS sheets would either create very complex assemblies or require gluing beforehand which would inhibit the hot wire cutting process downstream.

Regarding the cutting wires, the 0.25 mm one, as expected, produced much more precise cuts. It also resulted in material surfaces with a much smoother texture. The 1mm wire did not present evident improvements and produced a much coarser texture in the EPS that was not possible to avoid, even with increased cutting speeds.



Figure 4.17: Preliminary experiments, comparing hot wire cutting of different polystyrene foams, using different wires: a) EPS foam with 1 mm wire; b) EPS foam with 0.25 mm wire; c) XPS foam with 0.25 mm wire.

Considering these issues, all the prototypes in this chapter were fabricated using medium density EPS 150 foam blocks (Figure 4.18) and the 0.25mm nichrome wire. These blocks, with dimensions ranging up to 1 by 1 by 2 meters, were cut to to size, depending on the specific needs

of each prototype and are referenced throughout this dissertation as the stock volume.

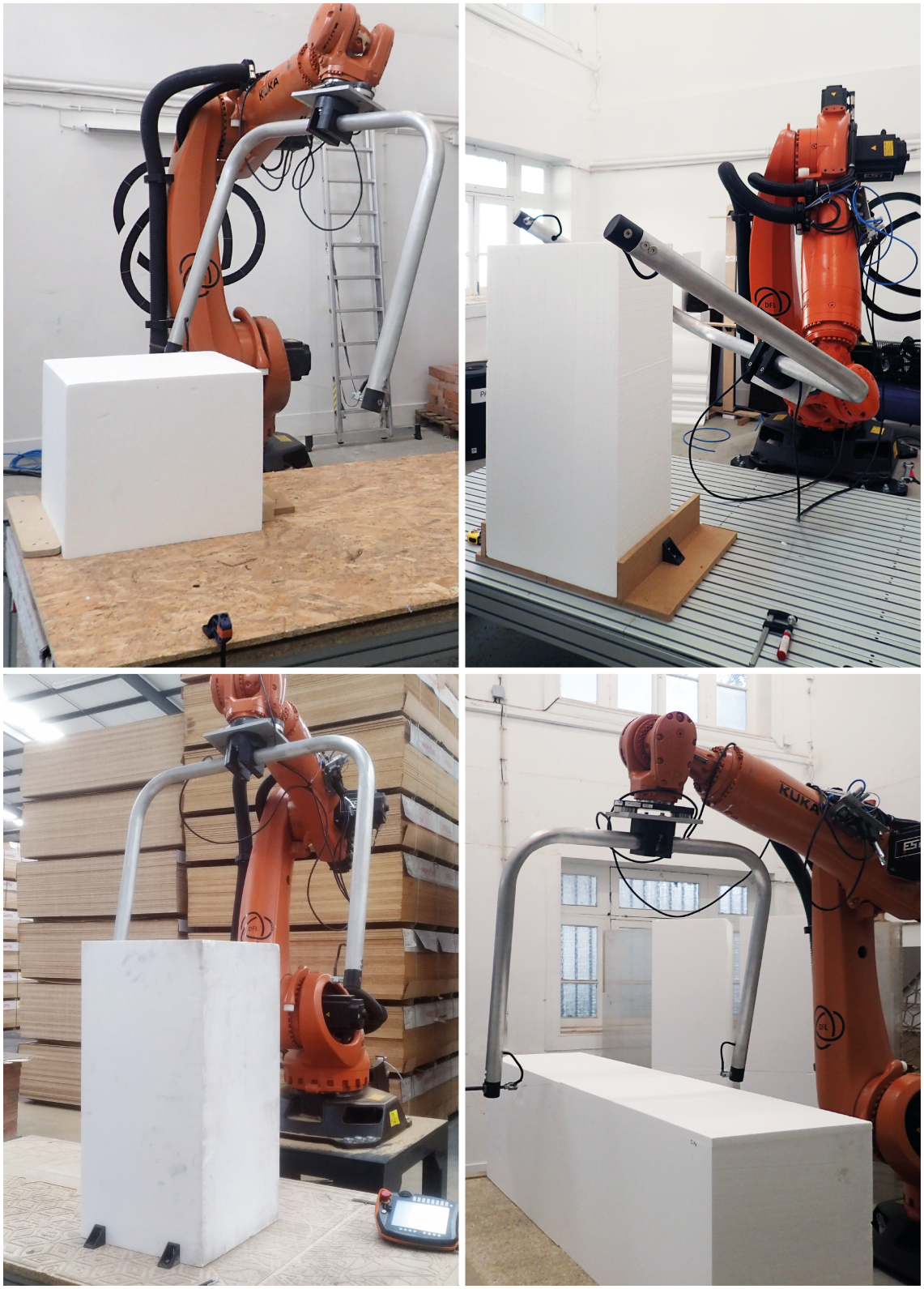


Figure 4.18: EPS stock material for main experimental prototypes developed.

4.2 3D milling vs RHWC

4.2.1 Objectives: RHWC characterization

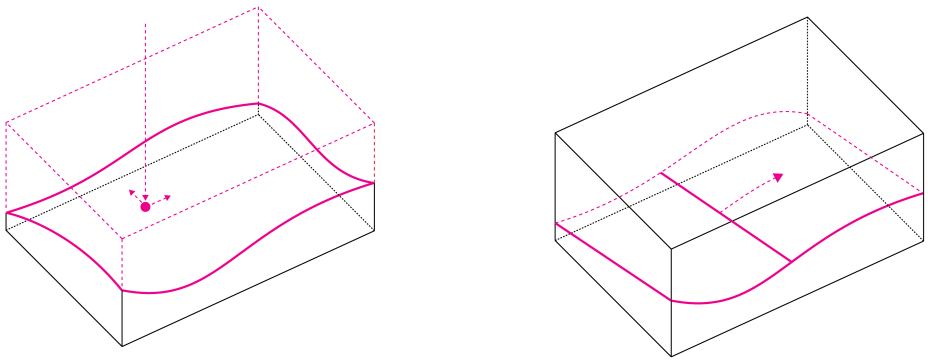
In the previous section, a general theoretical overview of RHWC was developed, describing the relevant hardware setup, materials and a basic example of the necessary code for robotic programming as well as general considerations of the process.

The RHWC vs 3DMill experiment presents the first practical approach to RHWC and proposes to fulfill two specific goals:

- To develop a practical working knowledge and characterise the RHWC process
- To directly compare RHWC with 3D milling.

Before moving further to the intricacies of using RHWC to produce concrete architectural elements, it is important to explore the material and technical features of this process. As introduced in the previous section, RHWC involves several variables, managing both digital and physical information. From defining a usable geometry, to translating it into robotic movement, to setting adequate cutting speed and temperature. All these variables are explored and measured in this first set of prototypes. Furthermore, this characterisation is done while simultaneously comparing RHWC with 3D milling. As described in (subsubsection 3.1.1.1), in general, indirect subtractive processes are the most common digital fabrication strategies already in use in the construction industry and *3D milling* of EPS formwork in particular is one of the most used processes for non-standard concrete architecture today.

The main differences between 3D milling and the 3D cutting process of RHWC lie in the point-based abrasive logic of the former and the linear slicing logic of the latter Figure 4.19. The first works by successively removing material, describing cutting paths at increasing depths in 3D space, point by point. The second operates by describing a 3D cutting surface in space, line by line, slicing out a volume of material. This general procedural difference has consequences in two major aspects: fabrication speed and geometrical freedom. When using such procedures in an EPS foam stock volume, both processes can nevertheless be used for the same purpose: production of concrete formwork. Nevertheless, 3D milling presents two key disadvantages: high production times and high material waste production. Two issues which RHWC proposes to address.



3D millng: point in 3D space RHWC: line in 3D space

Figure 4.19: The material/geometric transformation logics of 3D milling and 3D cutting with RHWC.

Thus, considering the relevance of 3D milling in practice and its proximity with RHWC, it is pertinent to compare RHWC and 3D milling to conclude on the apparent benefits of RHWC regarding these issues and to set a baseline for further experiments. By exploring both processes side by side, using the same geometry as input, it will be possible to extract clear comparative data from the resulting outputs.

4.2.2 Comparative setup

For the presented purposes, three EPS parts were fabricated, with specific geometries: two equal geometry pieces to directly compare RHWC and 3D milling and a third piece to more accurately assess geometrical limits of RHWC (Figure 4.20).

For parts A and B, to accurately compare RHWC and 3D milling, a very simple experimental setup and design was defined, focused on assessing the ability of either tool to correctly materialize an equal, pre-determined curved surface in EPS foam. For this purpose, two geometrical considerations were taken into account.

- It should be a double curved surface, with a small curvature radius.
- The surface should be able to be materialised through both processes, without any loss of geometrical features

Taking these into account, a very simple general ruled surface was defined, by sweeping a straight

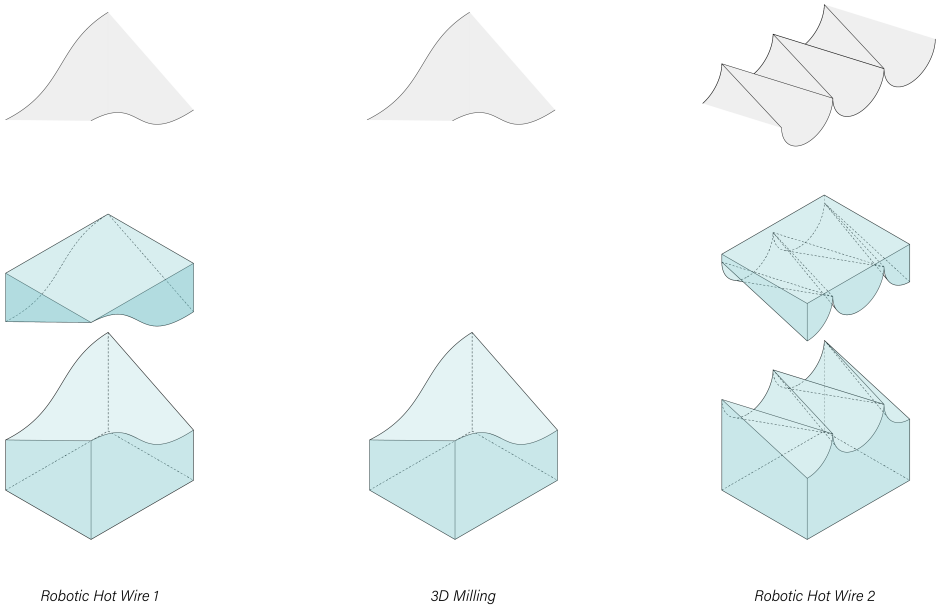


Figure 4.20: Three fabrication pieces for comparative study and characterization.

line (g) through 2 mirrored splines (d1, d2) (Figure 4.21 a)). This ruled surface condition met the basic criteria needed for direct fabrication in RHWC.

Although as discussed, 3D milling has in principle a larger geometrical freedom, RHWC can easily achieve smaller curvature radii and define overlapping surfaces not easily defined through milling. As such, the proposed surface curvature did not include any high curvature areas or overlapping details. The resulting waving double curved geometry, featured an area of 0.33m2 and a relatively low minimum curvature of approximately 250mm (Figure 4.21 a)).

As a general surface can be in any position in space, it is always necessary to define its placement inside a material volume to be transformed. This positioning can be relevant, particularly if not all of the faces of the volume are to be digitally fabricated and there is a necessary relation between the fabrication geometry and the existing material volume geometry.

In this case, the desired cutting surface was placed inside a stock volume of 500x600x500mm, aligning the straight rulings with the bounding box front side. This was done in order to theoretically obtain straight cutting lines when the hot wire enters or leaves the stock volume, which in turn could be used as an easy control for robot position calibration, wire tension and the overall precision of the cutting processes (Figure 4.22).

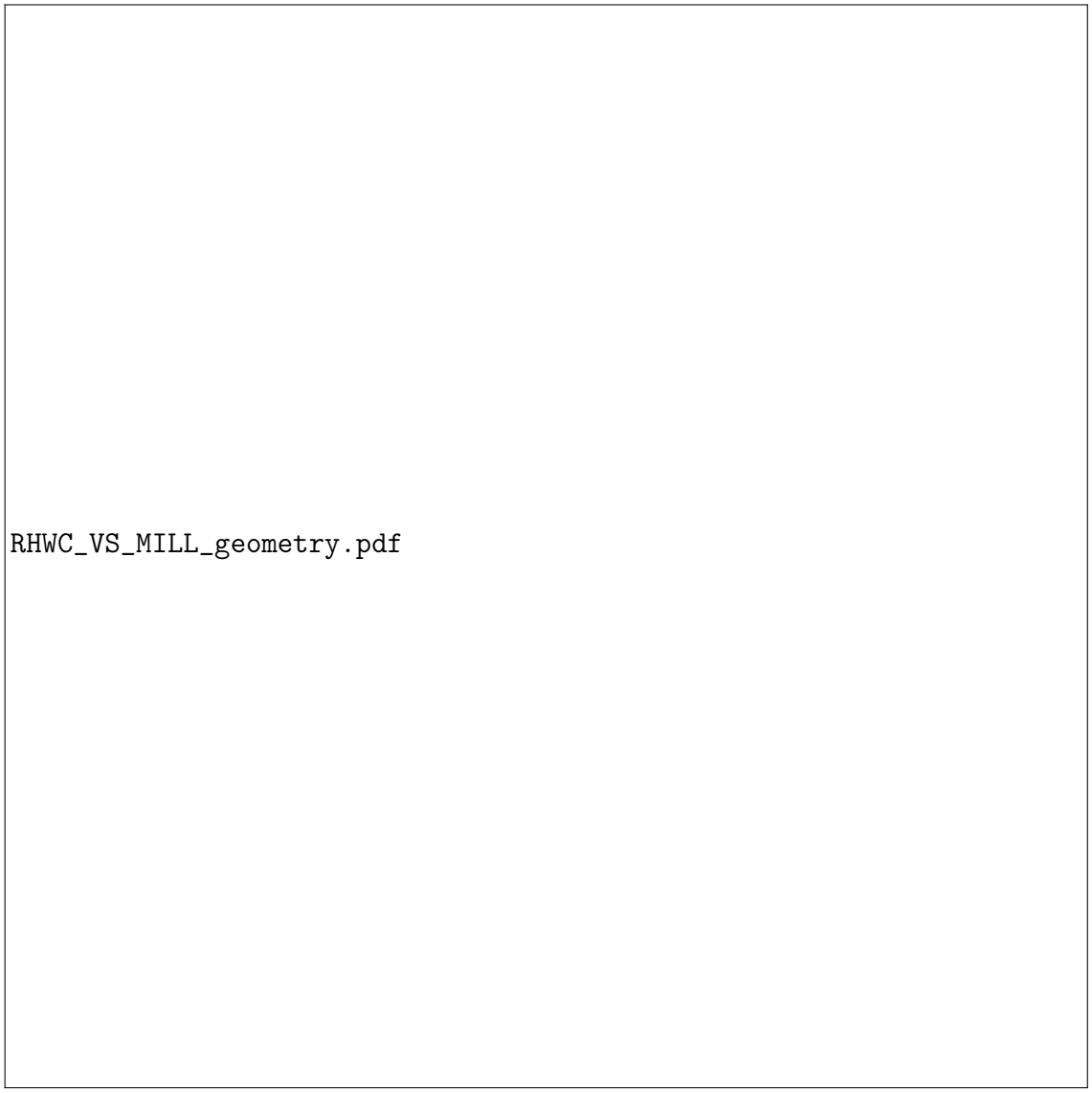


Figure 4.21: Ruled surfaces for RHWC and 3D milling. Geometry and curvature: a) parts A and B; b) part C.

For part C, a more complex surface was defined, aiming at better understanding the possible geometric limitations of the RHWC process, other than the ruled surface condition. For this reason, the proposed surface was composed of a set of alternating, tangent semi-conical surfaces, with vertices inside the cutting volume (Figure 4.21b)). The main issue in part C are the vertices of the conical sections which represent points where the hot wire will be stationary throughout large parts of the overall movement. As the hot wire cuts by melting material, this melting radius will increase depending on the time the wire takes to traverse the material. Stationary points are therefore, the worst case scenario for this issue.

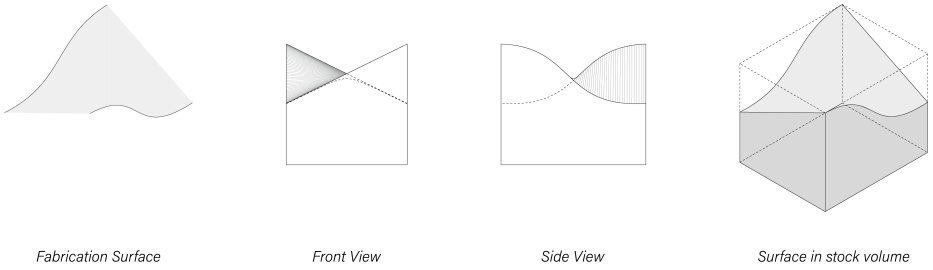


Figure 4.22: Design surface for parts A and B and its position in the stock volume.

4.2.3 Robotic fabrication

To fabricate part A, using RHWC, only one cutting pass was necessary to program, which was done using the KUKA|prc plugin for grasshopper, as exemplified in subsection 4.1.2. This was done by defining a toolpath for the wire to follow through the stock volume, described by 90 orientation frames (Figure 4.23 a)), using linear movements between them (LIN).

To control the movement of the hotwire and ensure that no collisions occur from its start position to the first cutting plane in the defined cutting surface and from the last cutting plane to the robot end position,[3] a set of offsets were used, in addition to the actual cutting tool paths. These offsets are dependent of the design geometry and were in this case, two tangent offsets, extending the surface 10cm on each direction (start and end) and 2 corresponding cartesian offsets on the z axis, before and after the extensions. This process was controlled, using the available simulations tools of the robotic programming software.

After programming and simulation of the robot movement, the stock material was placed in the working table and its position calibrated, using control points and custom check routines defined by vertical wire movements, parallel to the stock faces, also used to check for deviations in the EPS surface. The cutting program was finally run, taking approximately 37 seconds, from start position to end position (Figure 4.24).

[3] These movements from the robot start position and to the robot end position were Point-to-Point movements by default, which resulted in unforeseeable, very large sweeping motions of the already large hotwire tool and thus prone to collisions with the stock volume.

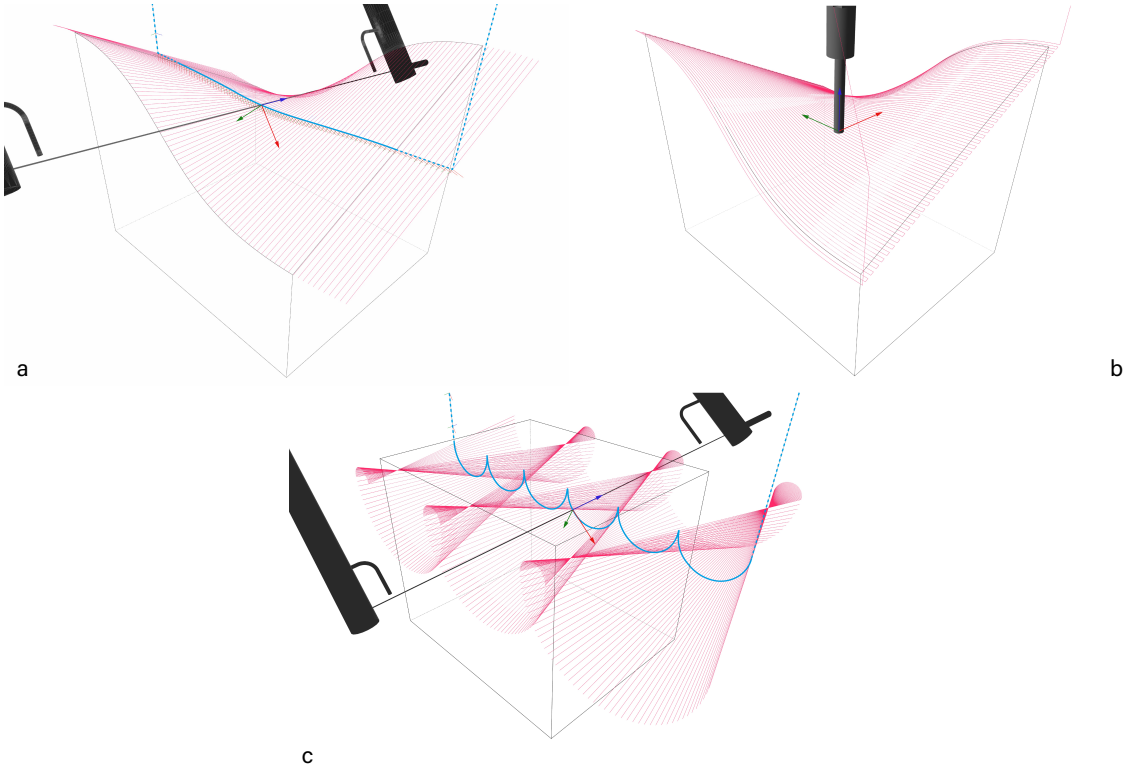


Figure 4.23: Tool paths: a) part A; b) part B (6mm stepover); c) part C. Hot wire cutting path in blue continuous line, hot wire approach offsets in blue dashed line; orientation frames for one tool point (xyz axis).

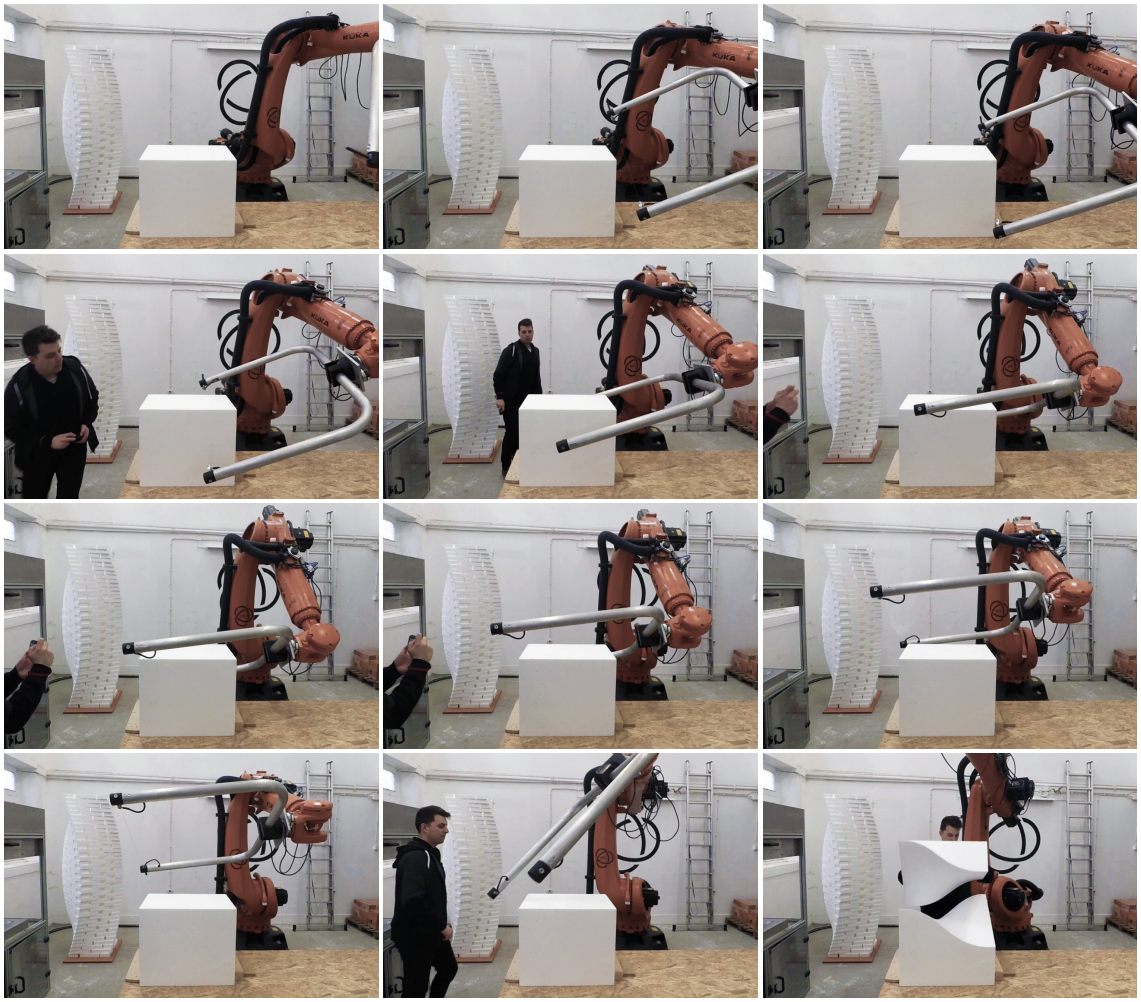


Figure 4.24: Wire cutting time-lapse for part A, including approach, cutting and exit.

To fabricate part B, a milling end-effector was applied to the same 6-axis robot, using a ball-point milling bit of 20mm in diameter 200m in length for increased milling speed. To achieve the same geometry of part A, several milling passes were defined with increasing resolution, a normal strategy for 3D milling. This results in rapidly achieving a low-resolution surface which is then refined in subsequent passes. In this case, first, 2 rough passes at 130mm and 10mm distance from the final surface, with 9mm between tool paths. Secondly, to achieve a surface quality comparable to the hot wire cut, 3 finishing passes were tested, with increasing density of tool paths (6mm, 3mm, 1,5mm between paths) (Figure 4.25). The tool paths for these passes were created by dividing the desired surfaces into parallel lines, alternatively linked to create one back and forth path through the whole surface (Figure 4.23 b)). Finally, some of these passes were experimented at different speeds to test different milling times and effects on the resulting EPS texture.

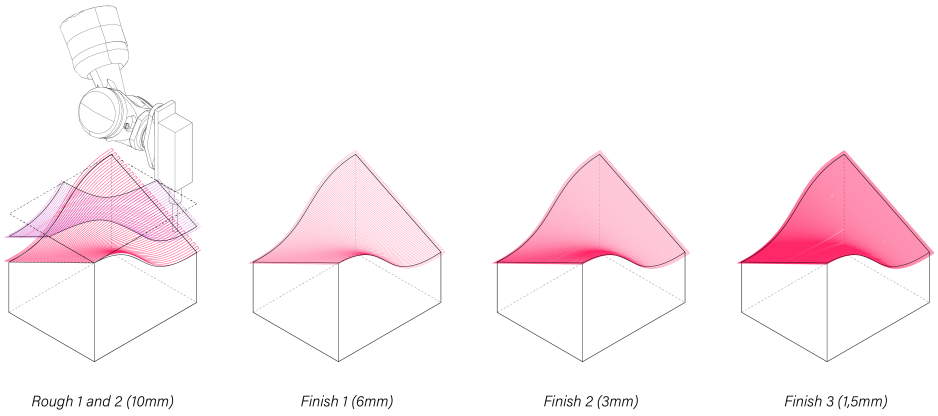


Figure 4.25: 3D Milling passes, with corresponding tool paths.

Actual cutting speeds were derived experimentally and the rough passes were fully completed in the times recorded in Figure 4.26. Considering the high milling times expected for the finishing passes, and the overall regularity and symmetry of the surface, the finishing passes were only partially completed and the execution times presented were extrapolated. The full process is illustrated in Figure 4.27.

Milling Pass	speed	stepover	time
Rough 1	50%	9mm	3m 4s
Rough 2	50%	9mm	6m 21s
Finish 1A	50%	6mm	5m 6s
Finish 1B	75%	6mm	3m 26s
Finish 2	10%	3mm	49m 8s
Finish 3A	10%	1.5mm	1h 47m 36s
Finish 3B	30%	1.5mm	32m 40s

Figure 4.26: Summary of milling passes for part B with extrapolated times.

The fabrication of part C followed similar principles to part A. One cutting pass, defined by the interpolation between orientation frames which created the hot wire tool path through the EPS volume (Figure 4.23 c)). For this case, considering the problem of cutting conical sections, the hot wire cutting speed and temperatures were reduced. A similar set of offsets were used, again to ensure that there were no collisions between the hot wire structure and the stock EPS volume. The full robotic movement is illustrated in Figure 4.28, highlighting the different high and low positions for the hot wire, as well as the different bow positions for the same vertex

point, representing the "stationary" position in these points.

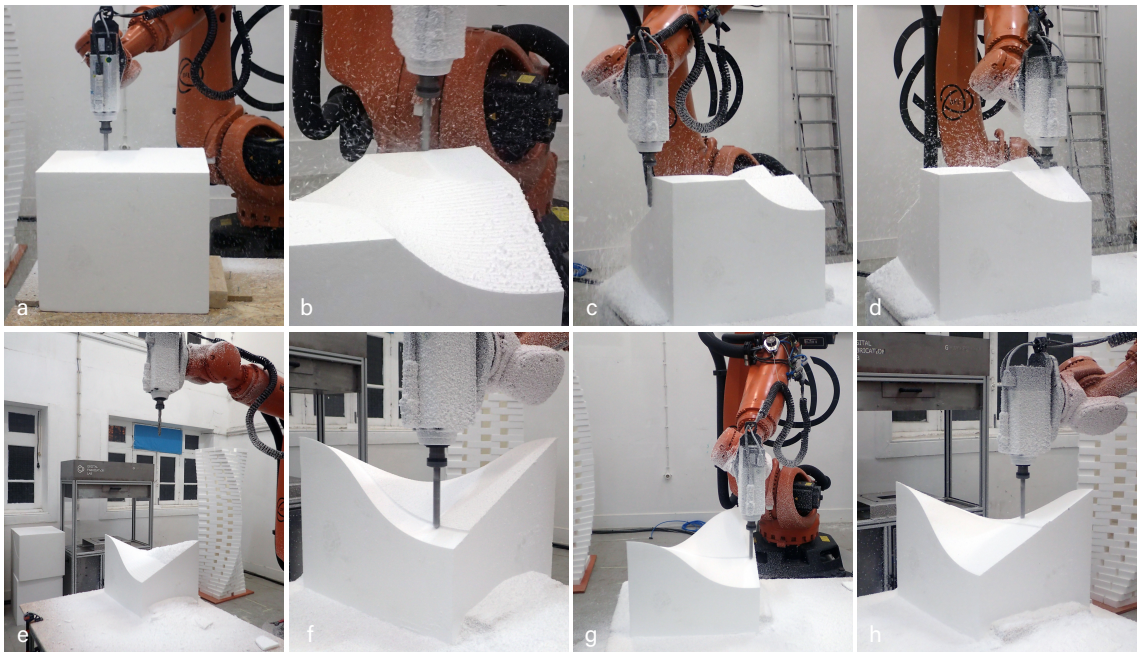


Figure 4.27: 3D milling process for part B : a,b) rough 1; c,d) rough 2; e) part after rough passes; f) finish 1; g) finish 2; h) finish 3.

4.2.4 Results and comparative analysis

Figure 4.29 presents a summary of experimental conditions and resulting data for all fabrication steps, focusing on material waste generation, fabrication time and resulting surface quality (smoothness). So, when directly comparing RHWC and 3D milling in parts A and B, several conclusions can be drawn. First and foremost, although in 3D milling we can quickly arrive at an approximation of the desired surface, when comparing similar surface smoothness (mill finish 3A), RHWC represents a reduction of about 2 orders of magnitude (hours to seconds), from 1h47m36s (rough+finish) to 37s. This sets a base speed of RHWC for generally continuous curved surfaces without complex geometrical features of approximately 1.8min/m2. In part C (cones), the fabrication time increased to 1m41s, which was a result of several factors: a longer path of the hot wire through the stock volume; an actual larger cutting area which produces more drag on the wire resulting in the necessity of a lower cutting speed to keep deformations to a minimum.

These measures only take into account direct fabrication times, thus other preparatory steps

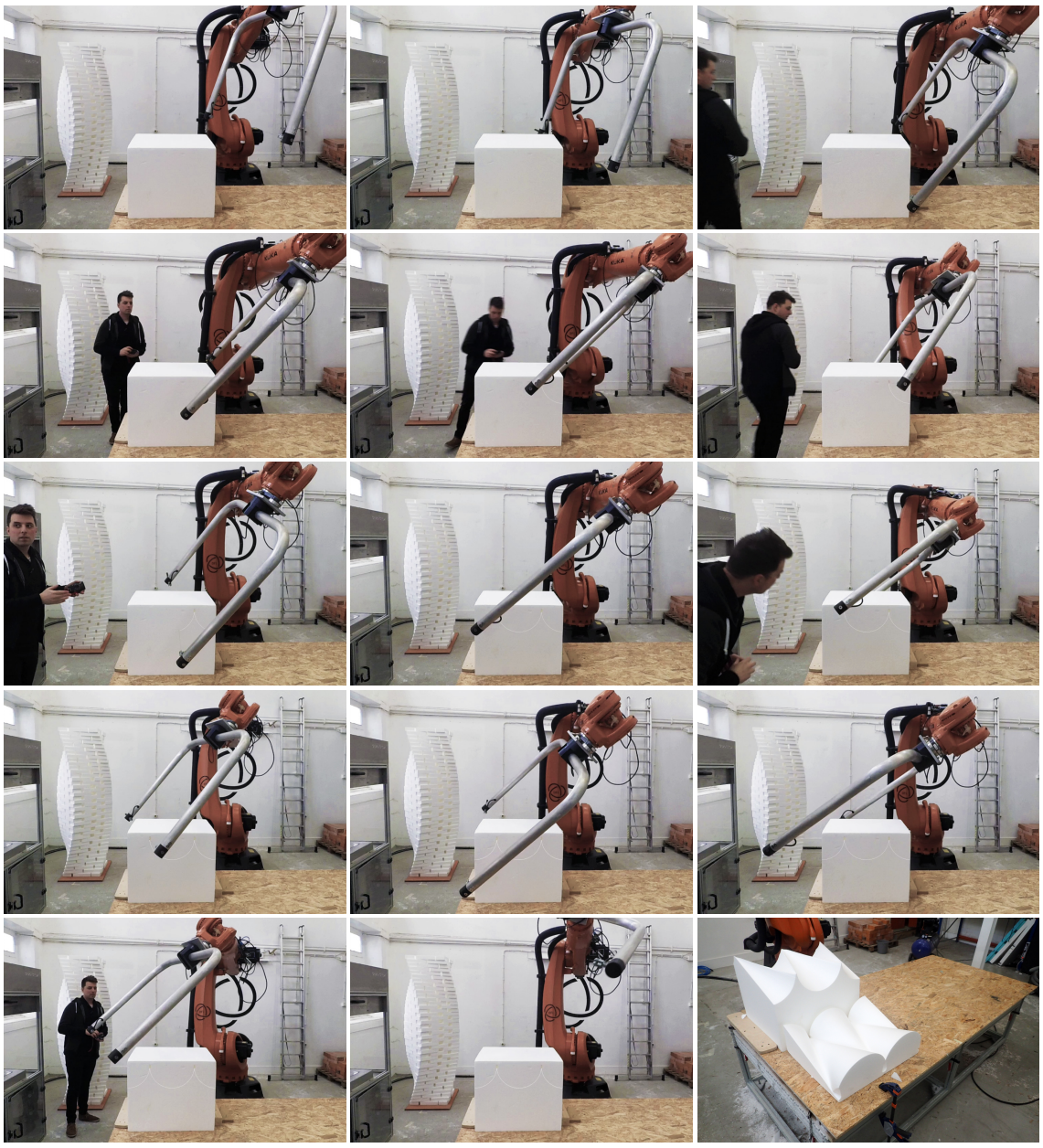
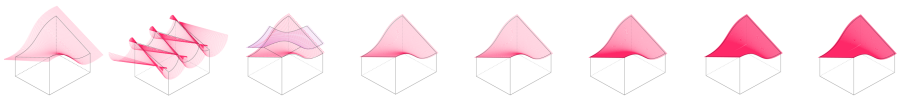


Figure 4.28: Wire cutting time-lapse for part C high and low positions of the wire throughout.



OPERATION	WAVE	CONES	MILL ROUGH	MILL FINISH 1A	MILL FINISH 1B	MILL FINISH 2	MILL FINISH 3A	MILL FINISH 3B
MATERIAL	EPS 150	EPS 150	EPS 150	EPS 150	EPS 150	EPS 150	EPS 150	EPS 150
STOCK DIMENSIONS	500X500X600	500X500X600	500X500X600	500X500X600	500X500X600	500X500X600	500X500X600	500X500X600
STOCK VOLUME	0.15m3	0.15m3	0.15m3	0.15m3	0.15m3	0.15m3	0.15m3	0.15m3
TARGET SURFACE AREA	0.33m2	0,492m2	0.33m2	0.33m2	0.33m2	0.33m2	0.33m2	0.33m2
KERF VERTEX (RHWC)	-	20mm	-	-	-	-	-	-
KERF GENERAL (RHWC)	2mm	2mm	-	-	-	-	-	-
WIRE DIAMETER (RHWC)	0.5mm	0.5mm	-	-	-	-	-	-
STEP OVER (3DMILL)	-	-	9mm	6mm	6mm	3mm	1.5mm	1.5mm
MILL BIT (3DMILL)	-	-	20x150mm ball	20x150mm ball	20x150mm ball	20x150mm ball	20x150mm ball	20x150mm ball
MOVEMENT TYPE	LIN	LIN	PTP	PTP	PTP	PTP	PTP	PTP
KUKA PRC INITIAL SPEED	1	1	45%	45%	45%	45%	45%	45%
CONTROLER SPEED	T1-20%	T1-10%	T2-50%	T2-50%	T2-75%	T2-10%	T2-10%	T2-30%
WASTE VOLUME	0	0	0.078m3	0.003m3	0.003m3	0.003m3	0.003m3	0.003m3
SURFACE QUALITY	5	5	1	2	2.5	3.5	5	4
CUTTING/MILLING TIME	**37s**	**01m 41s**	**6m 21s**	**5m 6s**	**3m 26s**	**49m 08s**	**1h 47m 36s**	**32m 40s**

Figure 4.29: Summary of experimental data for the 3 fabricated parts and intermediate stages (3Dmilling).

which can be similar for RHWC and 3D milling (e.g. materials handling and calibration) can bring these times closer together, at least within one order of magnitude. This time difference is, in itself, one of the key defining characteristics of RHWC.

The issue of surface quality is also of great relevance, particularly when the resulting surfaces are to be used for casting concrete, as was the case of the examples described in subsubsection 3.1.1.1 - 3D Milling. As any texture in the EPS will transfer into the concrete surfaces, usually several steps are used to insure a smooth finishing surface. In this case, RHWC was demonstrated to produce surfaces of similar finishing quality as 3D milling in a fraction of the machining time (Figure 4.30). In either case, if smoother finishes are desired, further manual or mechanic processes have to be used, such has sanding and coatings.

Finally, considering the issues of material use and waste generation, it is also clear that RHWC is a more materially optimized process. Not only does the hot wire cutting process yields two usable parts instead of one, the waste generated from the transformation process in itself is negligible (Figure 4.31a)). In the case of 3D milling, from an initial volume of 0.15m3, 0.08m3 were wasted in the form of EPS powder residue, representing in this case, over 50% of the total stock material (Figure 4.31b)). Without using other optimisation processes, this is always the case with 3D milling, as all of the excess volume, has to be removed to define the desired geometry.

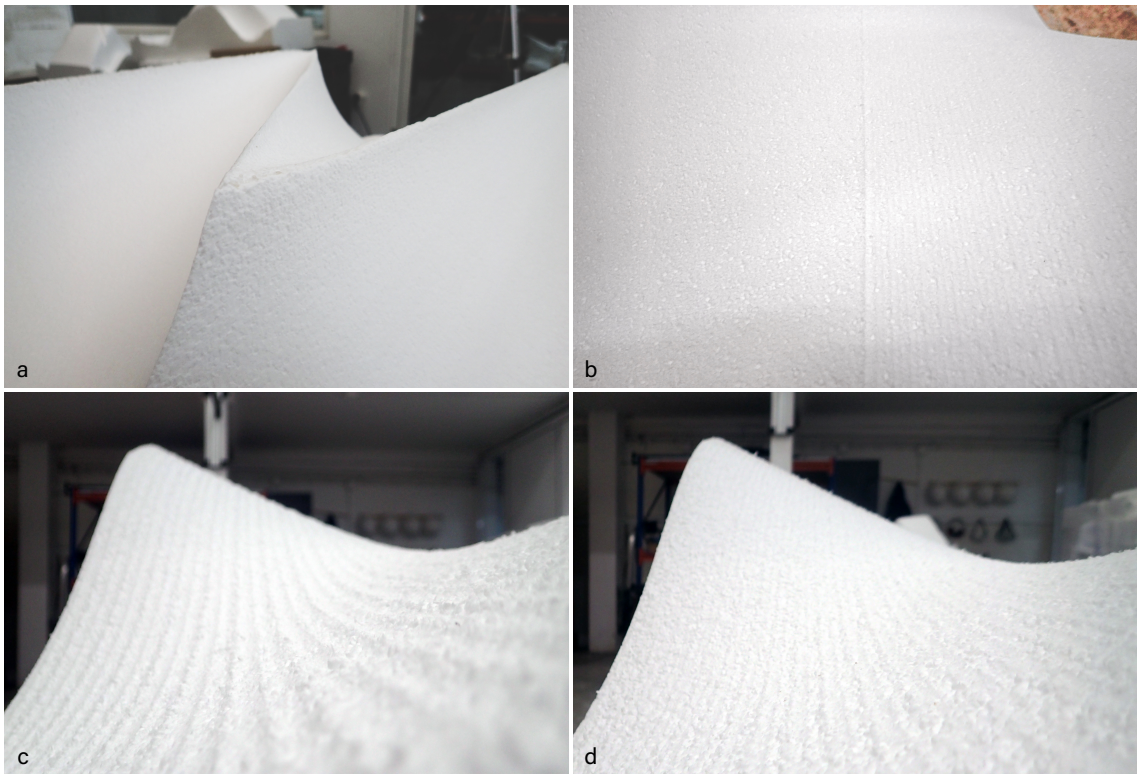


Figure 4.30: Hot wire cut and milling EPS textures: a) Hot wire cut from part C; b) CNC milling from 3mm and 1.5mm passes; c) milling from 9mm pass; d) milling from 6mm pass.

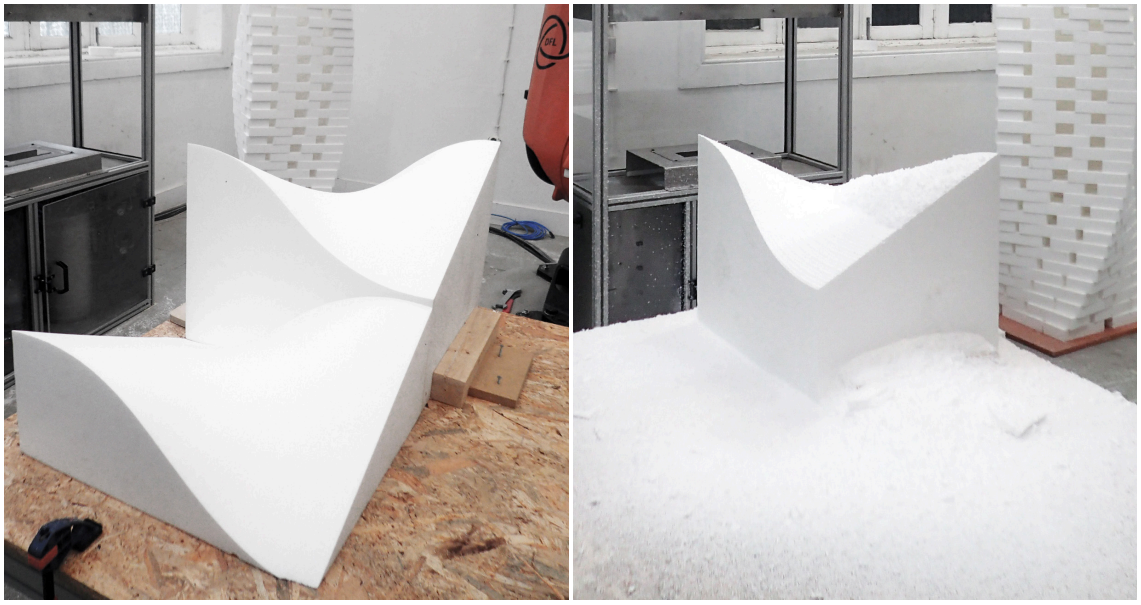


Figure 4.31: Material optimisation and waste generation in RHWC and 3D milling: a) RHWC part A; b) 3D milling part B (rough passes).

4.2.5 Practical issues of RHWC: speed, temperature and geometry

The previous analysis discussed some of the main characteristics of RHWC, in comparison with 3D milling based on a set of practical data. From these same experiments, further characteristics, specific of the RHWC process were made apparent and are explained here.

Speed and temperature in RHWC

With RHWC, one of the most critical parameters is the relation between cutting speed and temperature. Cutting speed, being the speed of the movement of the hot wire while cutting (established as a programming parameter and also controlled in real time during fabrication) and temperature, as the temperature of the hot wire while cutting. These two parameters work in opposition to one another, in combination with two other resulting issues: kerf and wire drag.

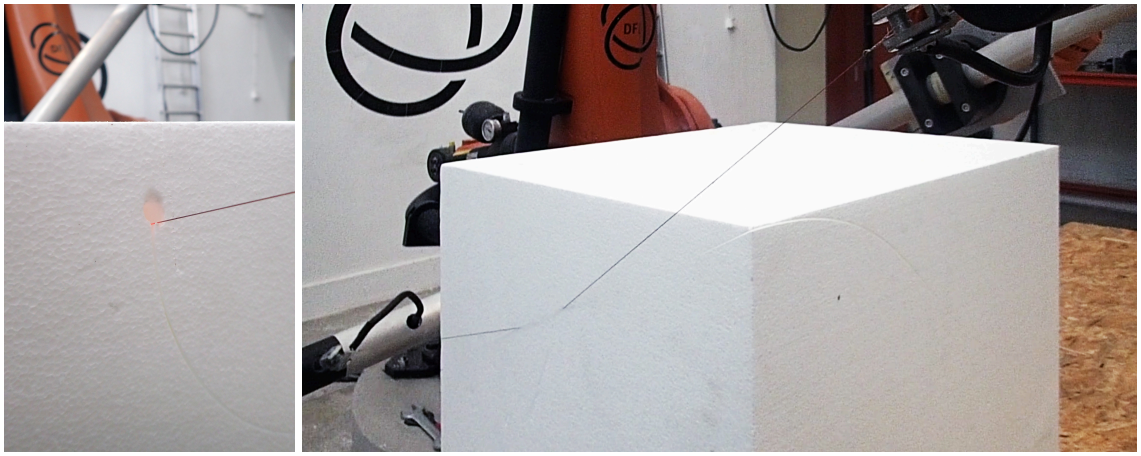


Figure 4.32: The issues of kerf and drag in RHWC: a) excess kerf by melting in a stationary point from the previous experiment; b) Wire dragging due to excessive speed/insufficient temperature, visible at exit point in failed experiment.

Speed and temperature are established at the beginning and the wire speed is the same as the robot speed before cutting. As the wire enters the stock material, depending on its density, it can slow down if the temperature is not high enough to melt the EPS foam in front, as it moves at the programmed speed. Wire drag is, in this context, the curving of the wire as the actual end-effector structure moves ahead while part of the wire is pushed back by the stock material (Figure 4.32b)). The end result of this effect, if not controlled, is that the actual cutting surface described by the now deformed geometry of the wire will be different than the programmed

cutting surface. Other parameters also affect this issue. For instance, the length of the cutting surface in the generatrix direction, as a larger cutting length will result in more drag being potentially produced in the wire.

A solution for this issue, can be to maintain the speed and increase the wire temperature. On the other hand, this can also have negative effects. As the temperature increases, the melting radius of the EPS foam, around the wire also increases, leading to an offset between the desired design surface and the actual cut material surface. This radius of the material which is removed is called Kerf and is a staple of all subtractive cutting processes, usually related with the width of material removed by a saw. In RHWC kerf corresponds to the melting radius of the wire which varies with temperature (Figure 4.32, a)) . The issue in this case is that in our experimental trials, increases in wire temperature would very quickly result in larger kerfs without allowing for substantially increased cutting speeds.

Another practical negative point of increasing temperature is related to the thermal expansion of nichrome wire. Like most materials changing with temperature, the nichrome wire has a relevant expansion along the wire length. This expansion can be calculated as a function of the initial length and temperature change of the nichrome wire, using the linear thermal expansion equation:

$$\Delta L = \alpha L \Delta T$$

In this equation, ΔL is the expansion size, α is the average thermal coefficient for nichrome $(1410^6/C)$, L is the length of the cutting wire (1m) and ΔT is the temperature variation between room temperature and the heated stage.

Using this equation we can arrive at values of around 5mm of expansion for the 350º - 400º used in the 1m wire. This change in length should be accounted for, using tensioning springs in the end-effector structure. Otherwise, it can contribute to a reduction of the tension in the wire, resulting in an increased drag and deformations while cutting.

To address these issues, an equilibrium must be found between all these parameters and effects to allow for precise cutting. Figure 4.33 presents the relation between the increase in the parameters of speed and temperature and the direct results in kerf and drag as well as the opposing parameters that are required for those potential increases. The equilibrium thus desired, in practical terms, should be one where the speed and temperature tradeoff should results in the maximum speed possible, for which there is no wire drag while also minimising kerf, enabling

fast but also precise cuts.

controlable parameters		*effects*			*opposing parameter requirements*	
		Kerf	Drag			
(increase) speed	>	-	+	>	+	temperature
(increase) temperature	>	+	-	>	+	speed

Figure 4.33: Relations between speed and temperature parameters and effects on kerf and wire drag. Opposing parameter requirements illustrate the necessity of increasing temperature as speed increases and vice-versa, in order to minimize adverse effects on kerf and drag.

Kerf and other geometric issues

Other practical issues also exist that have similar consequences regarding the ability to cut specific geometries with RHWC. These limitations stem from the particularities of the common RHWC conditions and the particular setup used already in this experiment and all others: cutting through heat, in a line, fixed to two points of an end-effector, which is in turn, affixed to a 6-axis robotic arm. These features result in the following limitations to the general rule of describing any ruled surface:

- **Size**: Both the wire (and corresponding RHWC tool size) and the robot's reach, limit the dimensions of possible cutting surfaces, particularly in the direction of the ruling lines, which are fixed by the wire and structure length. As such, the maximum cutting dimension in the direction of a surface generatrix is equal to the wire length and the maximum cutting dimension in the direction of a surface directrix is limited by the robotic arm's reach. Robotic systems can be enhanced with more axis of movement such as linear rails and rotating tables to combat this issue which otherwise implies subdivisions for larger surfaces.

- **Reach**: Although six axis of movement are a great increase in geometrical freedom when compared with other more limited CNC systems, for RHWC, the size of the end-effector and the rotation limits on each axis, can create unreachable points for large, continuous, complex curving surfaces (eg. helicoidal surfaces). This issue is compounded by the difficulty of stopping and resuming a cutting path without incurring in accidental excessive kerf.

- **Stationary points/lines**: Because in RHWC the cutting action works by heat and not abrasion, the longer the heated wire remains in the same point or line in space, the larger the kerf is. This has two geometrical consequences. First, any generalised conical surface or triangular surfaces will have in their vertexes stationary points that (if inside the EPS stock volume) will melt excessively. Secondly, for the same reason, acute changes in the moving direction of the wire will produce similar effects. The hot wire, while reversing direction, will slowdown or briefly stop for an instant, increasing the melting radius through this line thus diminishing the precision of the process (Figure 4.30 a)).

- **Continuous cutting surfaces**: Because the wire is a continuous cutting line, fixed to two points of a solid structure that cannot collide with the stock material, any movement of the wire must represent a cutting plane that fully traverses the stock volume. No partial cuts can be made in the direction of a ruling line. So, for instance, intersecting concave surfaces or recessed areas (e.g. a mould cavity) cannot be created from one whole block but can be assembled from several parts.

- **Voids**: voids in ruled surfaces are difficult to produce as the wire would either have to be disassembled and manually placed through the stock volume to then carve a perimeter shape or it would have to cut a path to the location of the desired void, through the stock volume, which might not be desirable. Some examples presented in subsubsection 3.1.1.1 - 3D Cutting, sidestep this issue by subdividing void areas in interlocking sections so that the voids are generated by joining two or more corner cuts.

4.3 The MSE Panels: Designing moulds for Hotwire cutting

4.3.1 Objectives: form, surface and composition for RHWC

Expanding on the first experiment which dealt mainly with characterising the methodologies of RHWC, this second experimental prototype investigates the particularities of using RHWC in the production of customized concrete formwork in a prefabrication context. It also focuses on the topic of expanding the architectural possibilities of lightweight precast concrete panels. The MSE Panels experiment explores a complete design, digital mould fabrication and casting process for a set of panels, based on the modular geometry of mechanically stabilised earth (MSE) retaining walls, adapted to a ruled double curved geometry.

This work builds upon some of the previous experiments with RHWC, already mentioned in (subsubsection 3.1.1.1) - 3D Cutting, by addressing the particular material implications of concrete cast with hot-wire cut EPS formwork. It also served as an introductory experiment to test, characterise and develop fabrication methodologies for RHWC moulds in a more realistic setting.

For this experiment, three challenges were identified, taking into consideration their relevance to concrete and RHWC. These three challenges arose from the three key concepts already discussed in this thesis, relating to form, surface and composition, aiming to directly explore the possible consequences of using RHWC in these dimensions at a basic level. The proposed challenges and concepts behind them were:

- Double-curved components (form),
- Textured components (surface),
- Variable materiality components (composition).

The first challenge addressed the overall problem of fabricating complex curved geometries, with the objective of further understanding the geometric constraints of the RHWC technology, specifically in the production of formwork for concrete. This issue was further divided in two specific problems. Firstly, the production of double-curved ruled surfaces with a particular high degree of curvature. Secondly, the materialisation of precast components with complex

perimeter designs, not aligned to ruling directions. With these compound issues as design objectives, we intended to "geometrically stress" the RHWC process.

The second challenge, addressing the issue of surface, focused on testing the textural qualities of simple EPS moulds and simultaneously on revisiting past examples of textured concrete (mentioned in chapter 2 and defined as post-processing) and exploring the specific aesthetic possibilities for textural surface effects, emerging from the hot-wire cutting process.

The third challenge, regarding the issue of material composition, was also two-fold. Firstly, to explore the adequacy of traditional concrete mixes to materialize the geometry of the proposed components. Secondly, to explore how the slicing logic of RHWC can enable the adoption of non-standard material composition in precast panels.

This idea stems from the fact that concrete is generally used in homogenous mixes in construction elements, that is, without any variation along any singular cast element. This fact corresponds directly to the prevailing culture in engineering and architecture, characterized by the discretization of functions between different elements (eg structure, insulation and coating). In opposition to this logic some examples could be found from the last decade of the 20th century onwards of engineered materials with non-uniformly distributed properties (Functionally Graded Materials-FGM), with various examples in concrete, particularly in direct concrete extrusion processes, as shown in (subsubsection 3.1.2.3) - Concrete Extrusion.

Nevertheless, other low tech examples exist in practice that take advantage of the casting process of concrete to achieve variable properties, such as the example the Roman Pantheon, already mentioned in Chapter 2 - Composition (subsection 2.3.3) as well as other more recent examples.

With this background, in the MSE panels, we explored this concept of a variable materiality in concrete elements, in which different zones of a single element can have different material performances. These could be either functional or aesthetic, by using different concrete mixes with sequential castings, a process enabled by the ease of creating complex, multi-part formwork solutions with RHWC.

To achieve all of the desired results, a fourth underlying objective of the MSE panels experiment, guided by all of the mentioned challenges, was the development of a mould system that enabled the production of any desired concrete shape within the RHWC slicing logic and its geometric and procedural constraints.

4.3.2 Prototype design

The overall design concept used for the experiments was based on the geometry of precast panels for mechanically stabilized earth (MSE) walls. MSE is a technology used for the construction of retaining walls capable of sustaining heavy loads, generally used in highways or bridges. A distinctive characteristic of this construction technique is the use of prefabricated modular concrete panels as exterior facing for the system. These are commonly quadrilateral or hexagonal, with or without interlocking joints, forming continuous, planar surfaces.

As it was not the objective to devise a new panel system for MSE, we used the geometry and modular concept of these panels, particularly the cruciform interlocking design seen in Figure 4.34, as a basis for this prototype, without taking into consideration any specific technical function.

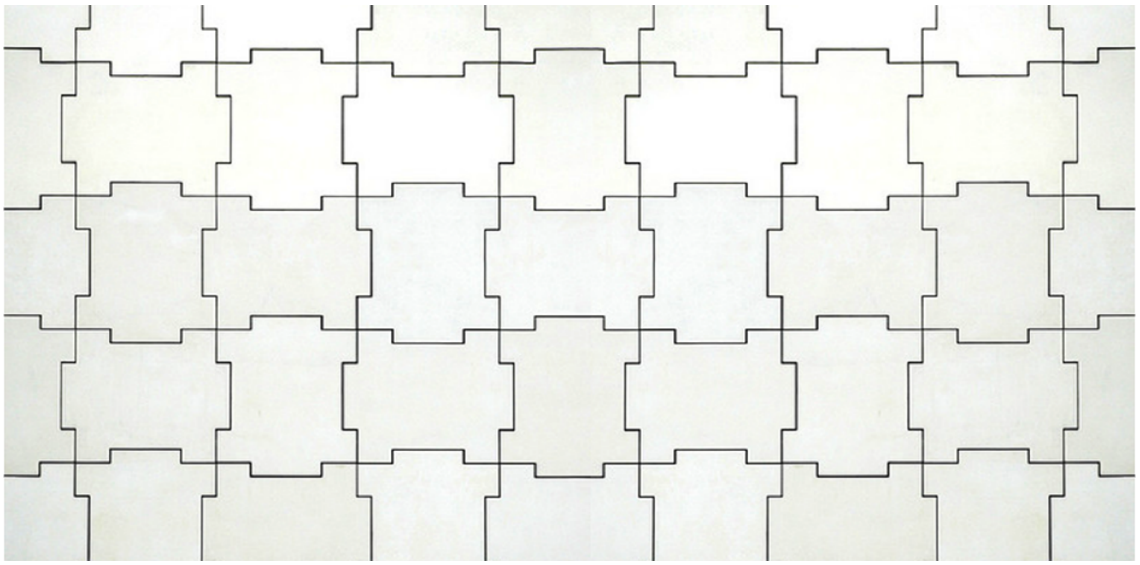


Figure 4.34: Mechanically Stabilized Earth facing with precast cruciform concrete panels.

To address the challenges previously stated, a double-sided, textured, ruled wall section was designed, spanning 7,4m, extracted from a large generalised, ruled surface that included a bending section with relatively small curvature radius Figure 4.35. Considering the first formal challenge stated, this geometry was designed to test the ability of the RHWC setup to accurately materialise highly curved surfaces. In comparison with real-scale examples, we consider that the curved surfaces of the MSE panels experiment are on the higher end of the spectrum. At it most curved point, the design surface achieved a local minimum curvature radius of 273mm.

The design surface was sectioned and panellised by projecting the cruciform modular panel design into it, resulting in an overall 15x2 grid of MSE panels. In order to further stress the geometric constraints for the fabrication, the projection direction and orientation of the 2D panel geometry used, ensured that the edges of the panels were not parallel to the surface ruling lines, creating a panel design with four curved perimeter edges. Front and back faces for the panels were defined as parallel, with a total panel thickness of 40mm, divided into 2 layers of 20mm. Finally the perimeter surfaces, comprising the thickness of the wall panels were also not perpendicular to the front and back surfaces.

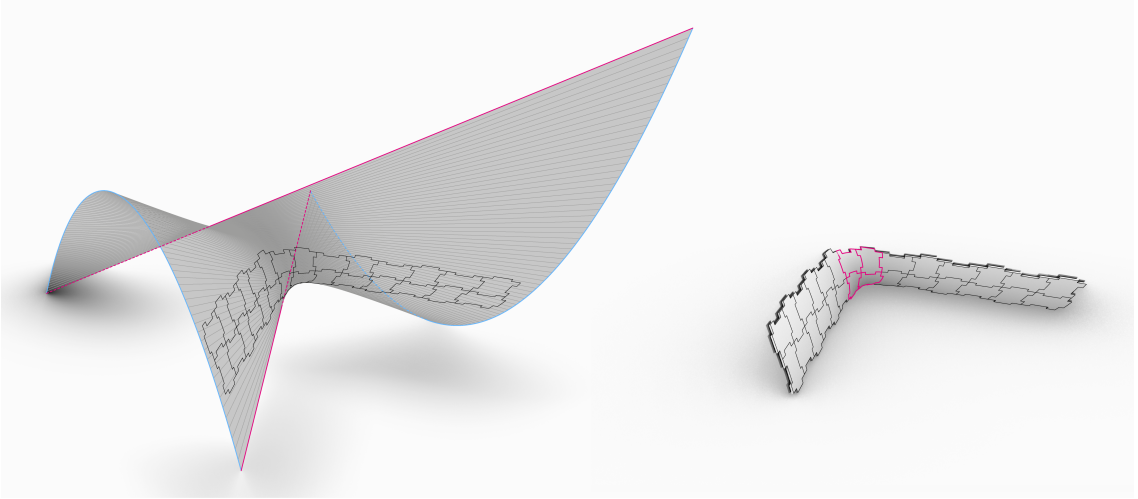


Figure 4.35: MSE general ruled surface and panel wall subdivision; selected panels.

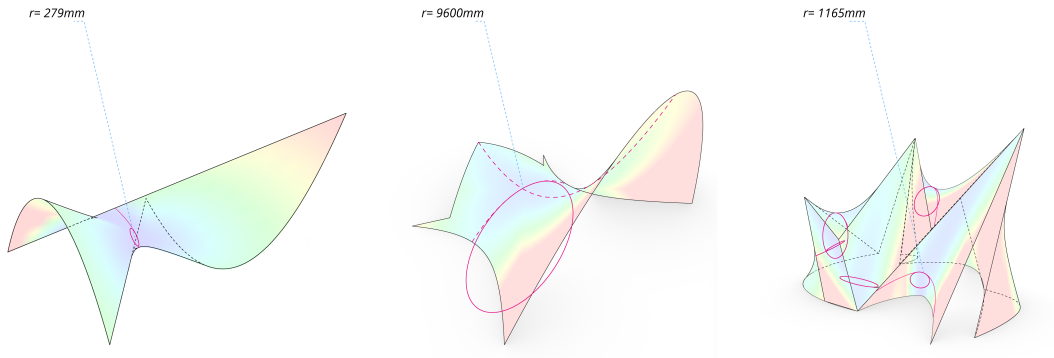


Figure 4.36: Curvature analisys for the designed MSE wall surface. Comparative analysis between a) MSE wall surface; b) Palmira Church by Felix Candela; c) Philips Pavilion by Jannis Xenaquis and Le Corbusier. 3D models not to scale.

To place the geometry of the MSE panels into context, Figure 4.36 compares the curvature of the general ruled surface used for the MSE panels, with two other examples already mentioned in chapter 3 - Form (subsection 2.3.1) which featured apparently highly curved ruled surfaces: the Palmira Chapel by Felix Candela, featuring a minimum curvature radius of approximately 9600mm and the Philips Pavilion by Jannis Xenaquis and Le Corbusier, featuring a minimum curvature radius of 1060mm. This analysis was performed by extracting and measuring the radius of the smallest osculating circles of the principal curvature lines of each surface in a 100x100mm grid.

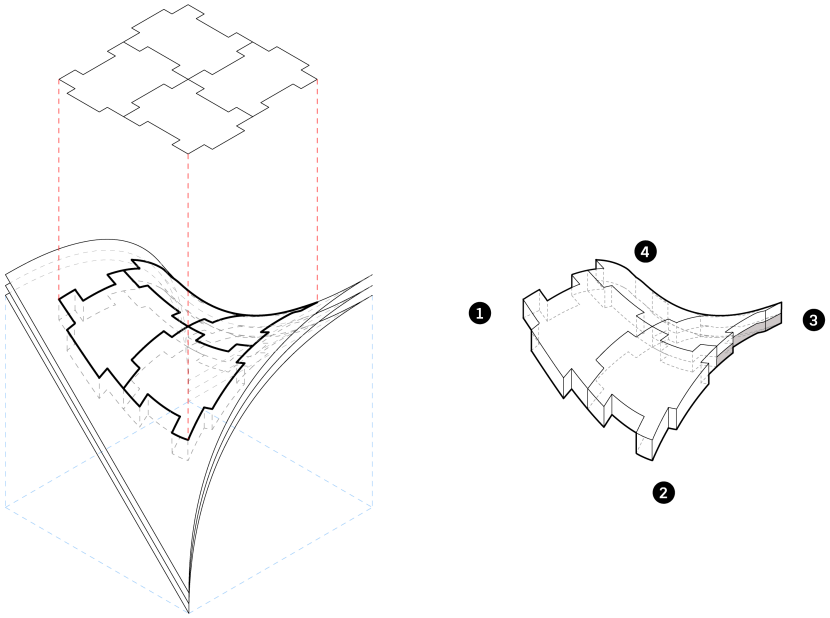


Figure 4.37: MSE panel modular geometry projection into three ruled surfaces (one per side and an interior one for panels with double composition) for the four selected panels and panel assembly.

From this base design, an assembly of 4 panels was extracted at the most curved area, to be materialised as an example of the system, with the boundary dimensions of 693x693x603mm and a surface area of 0.5m2 (Figure 4.37).

The panel design was further adapted in order for each panel to address particular experimental functions and test a wider set of characteristics:

- Panel 1 - non-textured panel with single composition
- Panel 2 - textured panel with single composition
- Panel 3 - non-textured panel with double composition
- Panel 4 - non-textured panel with double composition

Regarding the surface textural effects of panel 4, although a possibility, these were not predesigned in the general surface geometry. Considering the premise of extracting these surface effects from the actual RHWC fabrication constraints, this design stage was developed simultaneously with the robotic fabrication preparation stage.

Regarding the stated challenge of exploring variability in material composition, the wall was designed as a double faced panelling system, with the intention of defining different material properties for an imagined inside and an outside condition. These conditions could result in the application of different material properties of concrete, achieved with different mixes, with either aesthetic or funcional purposes. Characteristics such as color, surface quality, thermal insulation, sound insulation, density, etc could thus be achievable and modulated across different areas of an enclosure. In the specific case of the MSE panels, different colors were defined for each facing, to explore the feasibility of this idea. A 3d printed model of the 4 panel assembly is presented in Figure 4.38.

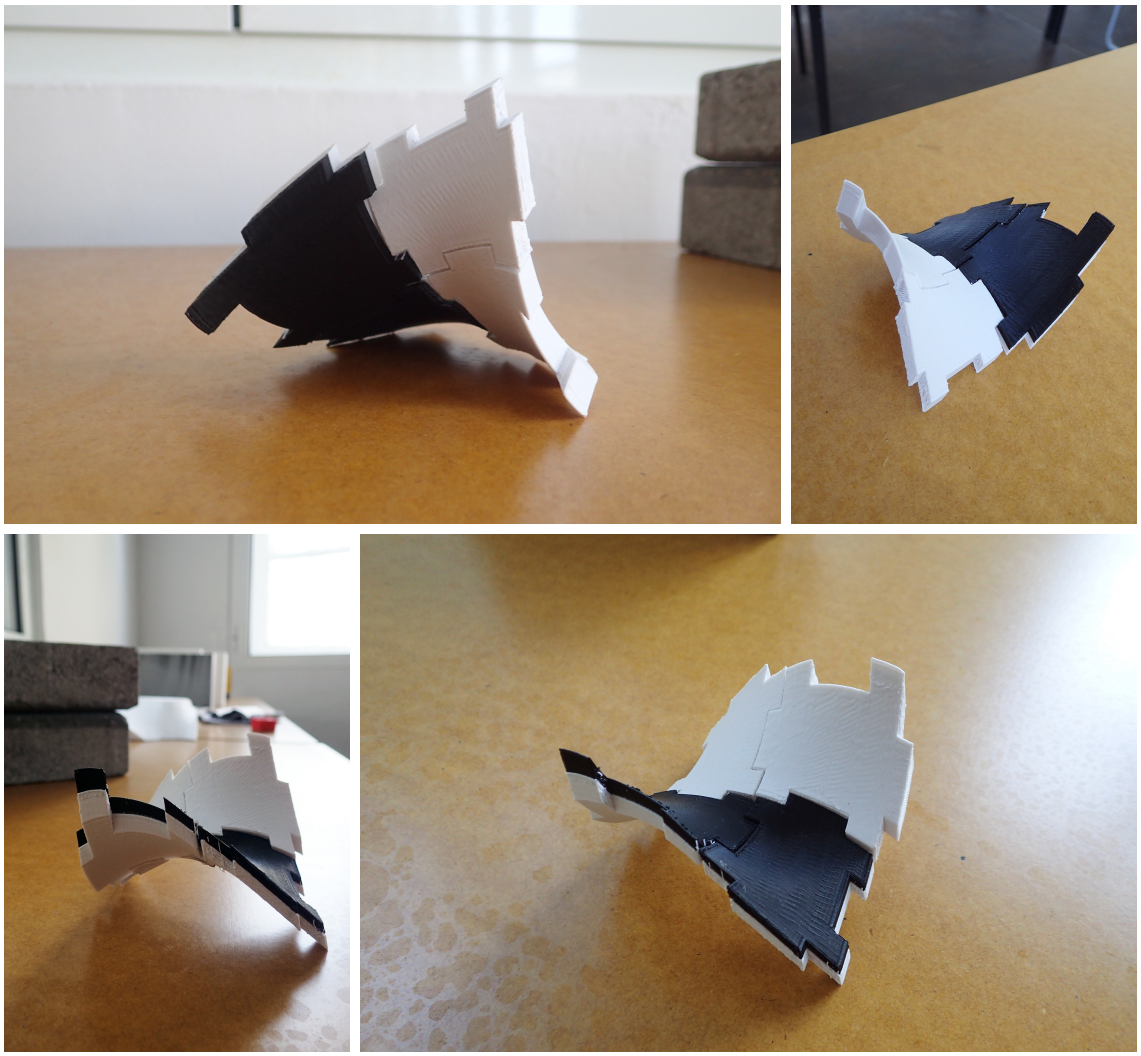


Figure 4.38: 3D printed test model for the assembly of the four MSE panels, with double-sided color variation.

4.3.3 Layered mould design

To develop the mold design for the desired MSE panel geometry, other EPS formwork systems were studied. The cases of the Zollhof Towers, the Louisiana Sports Hall Extension, discussed in (subsubsection 3.1.1.1) - 3D Milling, used open EPS moulds with cavities, for precasting concrete components. The spencer dock bridge case employed open moulds without any cavity for the continuous monolithic surfaces (Figure 4.39). So, while the last case, required only one surface to be milled, the moulds for the first two examples consisted of a similar surface within a bounding cavity which defined not only the overall surface geometry of the panel, but also its perimeter shape. This was possible due to the use of the 3D milling processes, which can create such geometries in the same milling operation. Furthermore, in all those cases, the concrete components were to be apparent on only one side and thus only one mould face was necessary.



Figure 4.39: Open faced moulds through 3D milling for the Zollhof Towers, the Louisiana Sports Hall Extension and the Spencer Dock Bridge.

As expressed in (subsection 4.2.5) - Practical Issues of RHWC, mould designs such as the first two examples are not directly possible in one piece as the slicing operations of RHWC cannot produce encased cavities and can only produce continuous surfaces. Moreover, because of the proposed geometric complexity of the MSE panels that included a complex perimeter shape and the need to accommodate double-faced components, a completely encased mould system was deemed necessary. With these limitations and objectives considered, a layered mould system was devised, that took advantage of the ability of RHWC to create several cuts from a single piece, without destroying stock material.

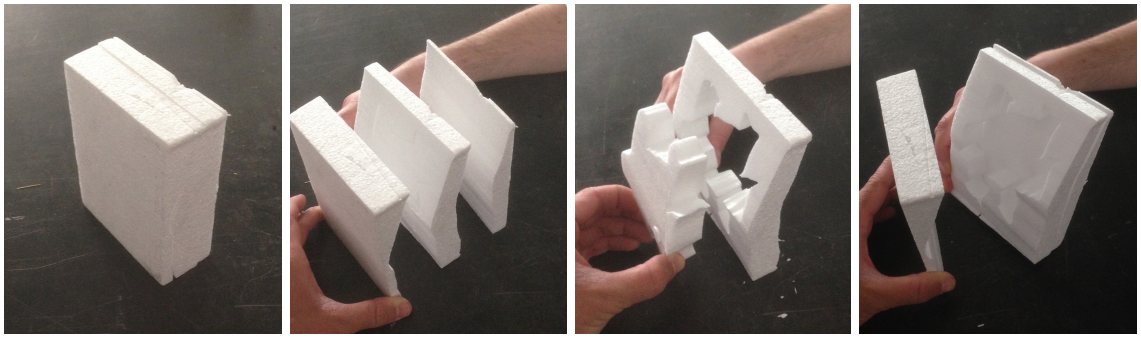


Figure 4.40: Layered mould design prototype: a) assembled system; b) three main parts (front surface, core, back surface); c) detail of the core perimeter carving; d) detail of the interior void.

The layered mould system (Figure 4.40) was defined in its general case as a three part system, fabricated from a stock EPS volume and composed of:

1. Front part
2. Back part
3. Core part

Front and back parts define the overall untrimmed material surface geometry of the respective sides of a theoretical panel. The core part corresponds to the resulting part between front and back surfaces and can contain a void with the desired shape for the panel geometry. A pouring channel can be carved into this core part for casting and all components can be easily assembled and secured.

Each of these material surfaces can be created through one hot wire cutting pass, all from the same stock EPS block, without the need for any assembly between steps. Moreover, because of the core perimeter part, separating the top and bottom surfaces, these can have different geometries, allowing for the creation of panels with non-parallel surfaces on both sides.

The moulds for all the MSE panels were designed using this strategy, differing in dimensions and perimeter geometry. Due to time constraints, from the original set of four, only panels 1, 2 and 4 were actually materialised. The bounding box dimensions for the three fabricated panels were 308x385x385mm, 308x385x445mm, 220x555x390mm, defined in accordance with the available EPS stock blocks (1000x500x350mm) and also taking into consideration a minimum perimeter margin of 50mm to withstand the pressure of the concrete pour in the closed mould design. The 3D modelled components were oriented in the stock volume geometry taking these needs

into consideration and with the objective of minimizing material waste, accommodating to the smallest stock volume width possible. The final mould geometry was tested by 3D modelling the actual final sliced mould parts (Figure 4.41).

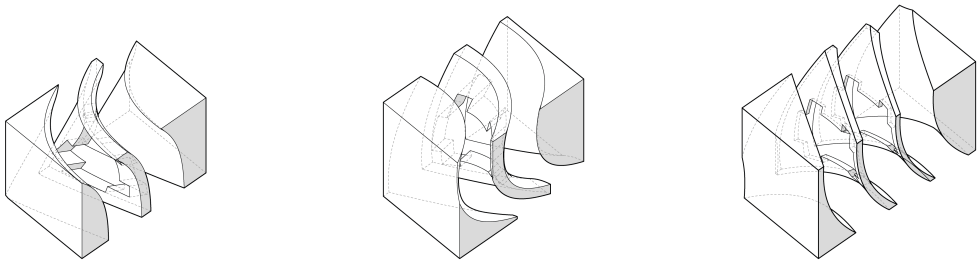


Figure 4.41: Mould geometry for panels 1, 2 and 4.

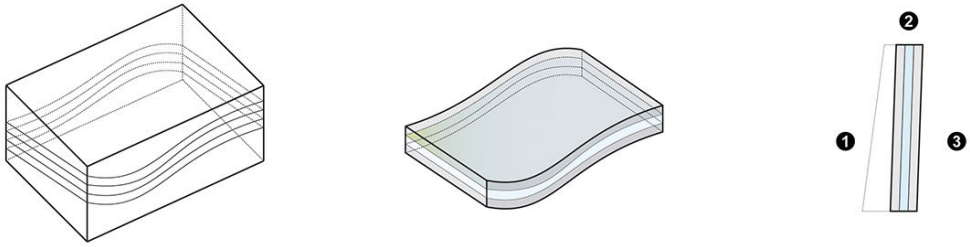


Figure 4.42: General example of three sections of a layered mould design for a double faced panel with an interior insulation core, without a custom perimeter. In this general case, there are three core parts which could be iteratively removed and cast to create a single panel.

The layered composition proposed for panel 4, and the required mould parts for it were achieved by taking advantage of the non-destructive slicing logic of RHWC and the layered mould design. This merely implied a further subdivision of the general perimeter and core part into two. Thus, these four-part layered moulds can allow for the casting of separate concrete mixes. Using this mould design, one can cast multiple layers in sequence as the first mix can be cast within the void from the first core and the second mix can be cast by removing the second core and creating a new void for casting, adjacent to the already cast part. In theory, this process could be repeated for more than 2 layers and possibly including interior cores of other materials such as insulation. Figure 4.42 presents a general case of this logic of casting in voids by sequentially removing core parts.

4.3.4 Robotic fabrication

The robotic simulation and toolpath generation for the hot wire cutting of the EPS moulds for the MSE panels was done in the Grasshopper plugin for Rhinoceros, using the KUKAprc software, developed by the Association for Robots in Architecture, as outlined in subsection 4.1.2 - An algorithm for robotic hot wire control.

With the panel subdivision created, all panels 3D modelled, and each nested inside a stock volume, general cutting surfaces (CS) were created for each side of the panel thickness and the perimeter shape of the panels to create the necessary cutting paths. The movement of the hot wire was programmed by extracting two points for each ruling of the cutting surface plus a third for the orientation angle of the hot-wire structure. Start and end offsets were added to control the exit of the wire from the stock volume and to better avoid collisions of the large end-effector. This process was repeated for each cutting surface, and simulated using the available KUKAprc collision checking, as well as with dry runs for the cutting routines. Figure 4.43 shows the cutting surface (generatrixes), toolpaths and corresponding robotic movement simulation for the outer surface of panel 1.

The textured geometry of panel 2 was designed directly from the tool path definition. Using the original cutting surface for the panel, and the same number of ruling subdivisions as the other panels, the center of the generatrix lines was maintained, while one of their endpoints was moved, away from the original surface. This was done in an alternating fashion, with a set frequency, and amplitude resulting in inclinations of the wire from the original surface and thus resulting in a textured effect.

Several simulations of this wire texture language space were tested on the MSE panel design, varying the frequency of alternating points, which created smaller or larger waves, varying the movement distance of the points, creating higher or lower waves (Figure 4.44). Other tests were also conducted, varying the center point of the wire which defines a virtual line which remains flat throughout the surface (Figure 4.45)

After these experiments, two solutions were used, featuring approximately 30 mm of offset, every 30 mm and 10 mm of offset, every 5 mm, representing larger and smaller textural effects to better understand the material boundaries of this vocabulary.

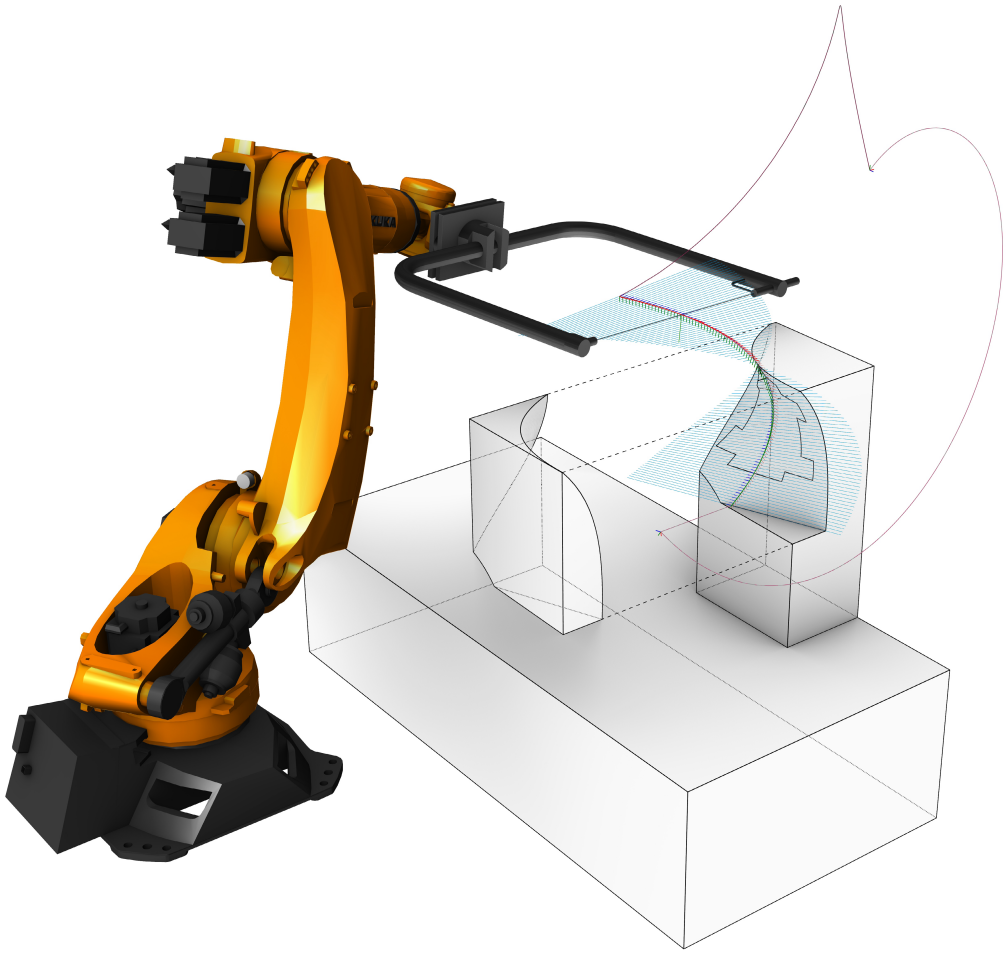


Figure 4.43: Cutting surface representation and simulation of section for 1st sweep of panel 1 of the MSE panels.

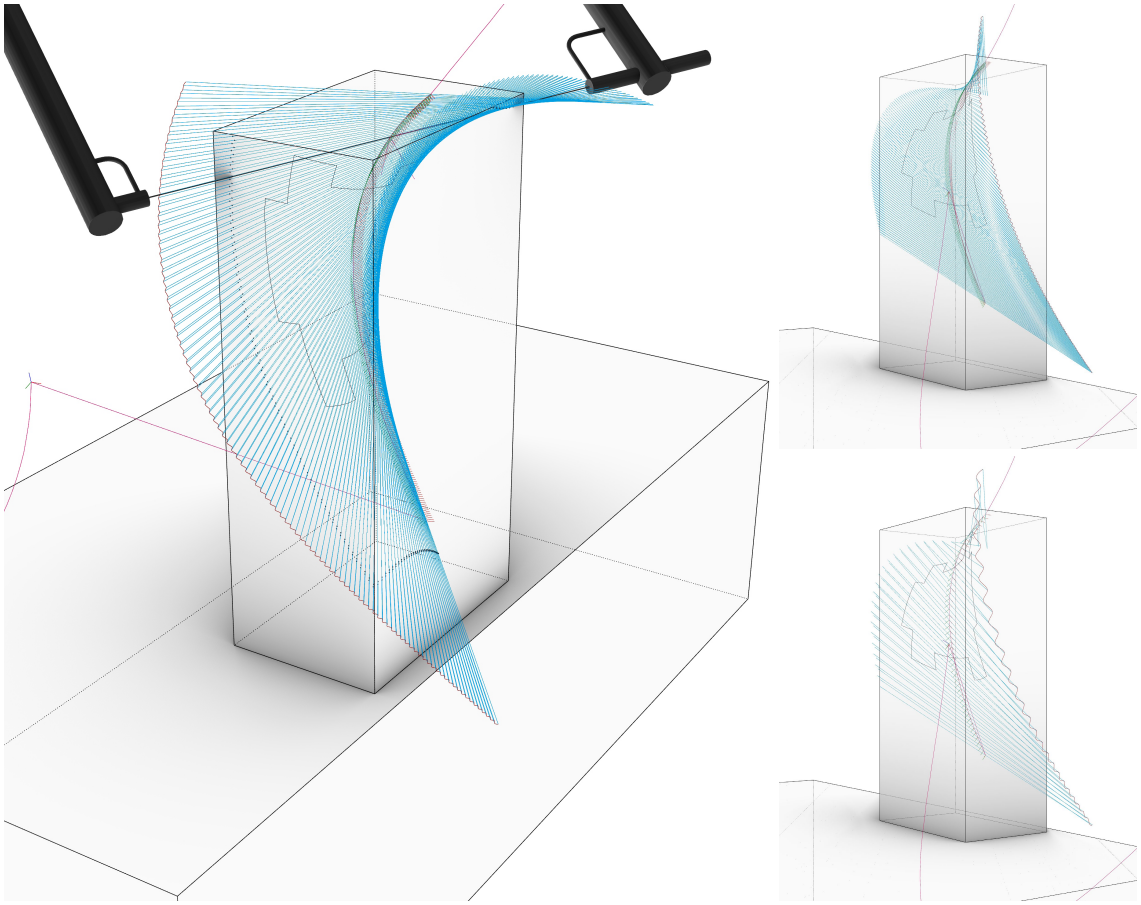


Figure 4.44: Simulations for panel 2 textures by modifying tool path number and offsets: a) 5mm amplitude to 5mm frequency; b)10mm amplitude to 5mm frequency; c) 30mm amplitude to 30mm frequency.

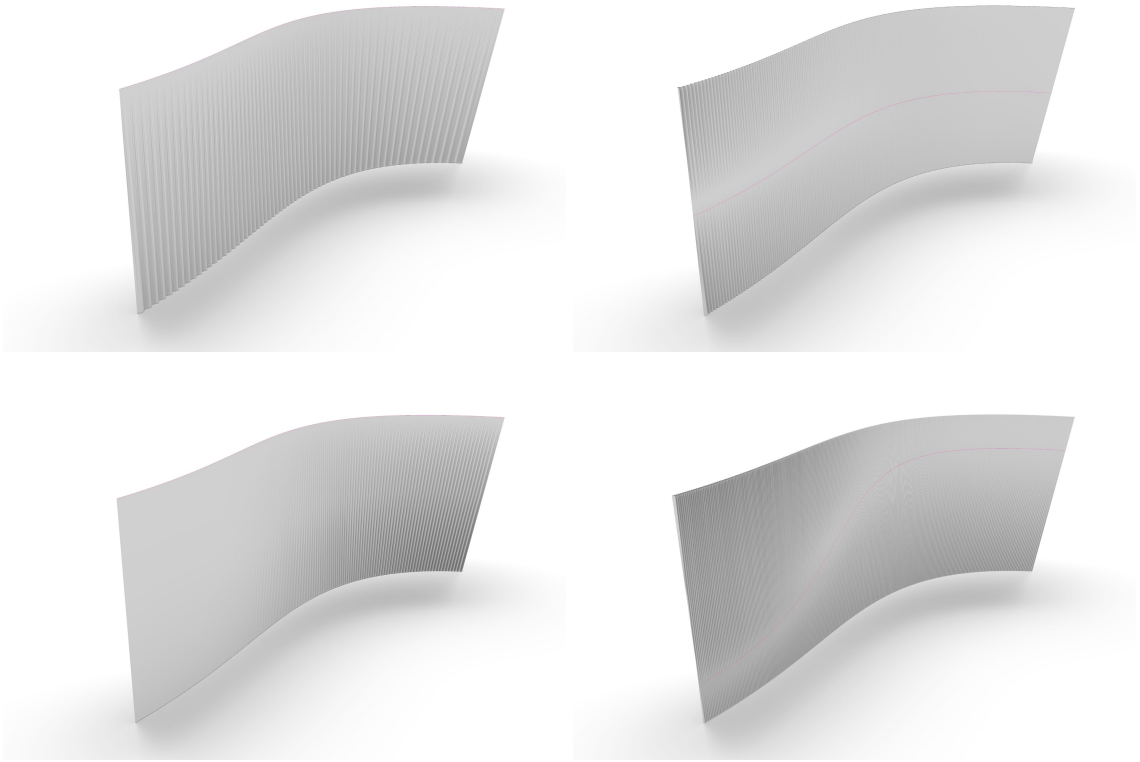


Figure 4.45: Wire texturing vocabulary tests: a) top alignment; b) center alignment; c) amplitude gradient with top alignment; c) variable center point along predefined curve.

Concerning the robotic fabrication process of the moulds, our RHWC setup didn't feature any advanced calibration and feedback mechanics for wire temperature. As such, a baseline for the relation between speed and temperature was established through trial and error in preliminary experiments, with the sole optimisation parameter being achieving the fastest cutting speed, while simultaneously minimising kerf and reducing drag to zero. (Figure 4.46 a),b)).

A relatively low overall speed and temperature were used in order to increase the accuracy of the cutting process as it was verified that higher temperatures would quickly increase kerf radius but speed could not be increased past a point, without incurring in wire deformation, even when increasing temperature. As speed differences to CNC milling were already substantial, as tested in the previous experiment, an overall speed of 10mm per second generated the best results, reducing the maximum kerf size to aproximately 1.5 mm, with an adjusted temperature to eliminate wire dragging. The speed and temperature parameters were closely monitored in the final cuts, due to the diversity of cutting situations and respective speeds necessary for the proposed geometry.

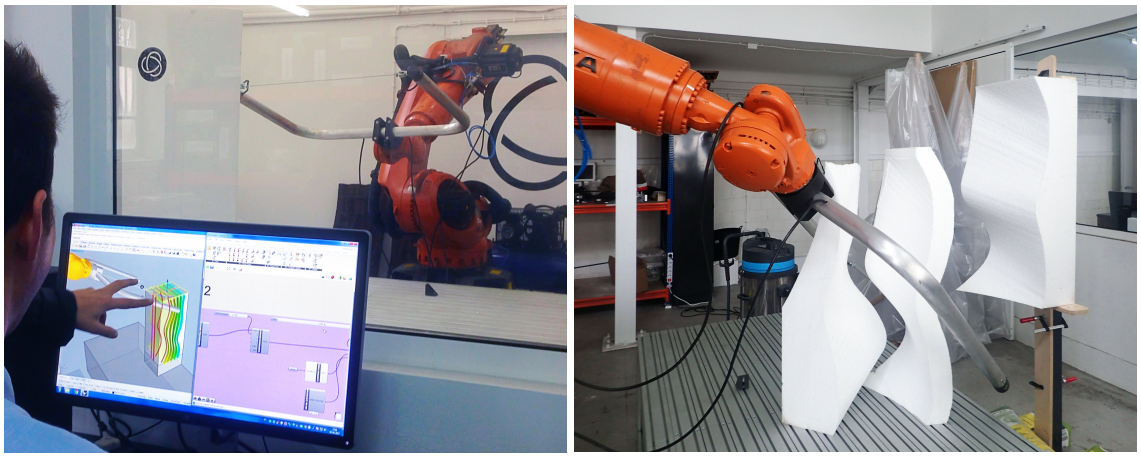


Figure 4.46: Preliminary experiments to test the cutting parameters of speed and temperature for the MSE experiments. a) setup; b) multiple test cuts.

Using this setup, and the programming described earlier, the final cutting routines consisted of 4 cuts for panels 1 and 2 and 5 cuts for panel 3. The first cuts carved the front and back general ruled surfaces from the EPS stock block, followed by the cutting of the central void in the remaining piece (Figure 4.48). The entrance and exit trajectory for the perimeter/void cut became the concrete pouring channel. A final horizontal cut trimmed and separated all the parts of the mould. Cutting surface diagrams of the mould for panel 1 are presented in Figure 4.47 and the general full set of robotic operations for the fabrication of the MSE moulds was as follows:

1. Stock check: vertical wire movement, tangent to two perpendicular faces of the stock volume, to align on the cutting table and check for any initial material deviations.
2. Cut 1: front face cutting pass and removal of the resulting block.
3. Cut 2: back face cutting pass and removal of the resulting block.
4. Cut 3: perimeter cut, including the casting channel
5. Cut 4: core thickness cut, dividing the central piece into two (panel 4 only).
6. Cut 5: assembly of all cut parts, and horizontal undercut, separating the core parts from the excess stock volume and levelling all parts.

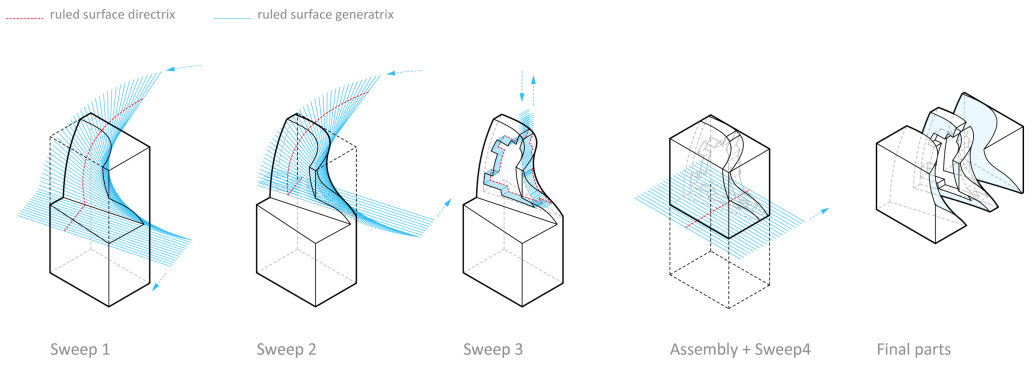


Figure 4.47: Cutting routines for MSE panel 1 and final mould geometry.

The four cuts (panels 1 and 2) and five cuts (panel 3) necessary for each complete formwork system took on average approximately 7 to 10 minutes, including the intermediate removal and assembly steps necessary. Figure 4.50 illustrates the complete process for the MSE panel 4 mould parts as well as the finished moulds for all three panels. Figure 4.49 ilustrates the main cutting operations for textured panel 2.

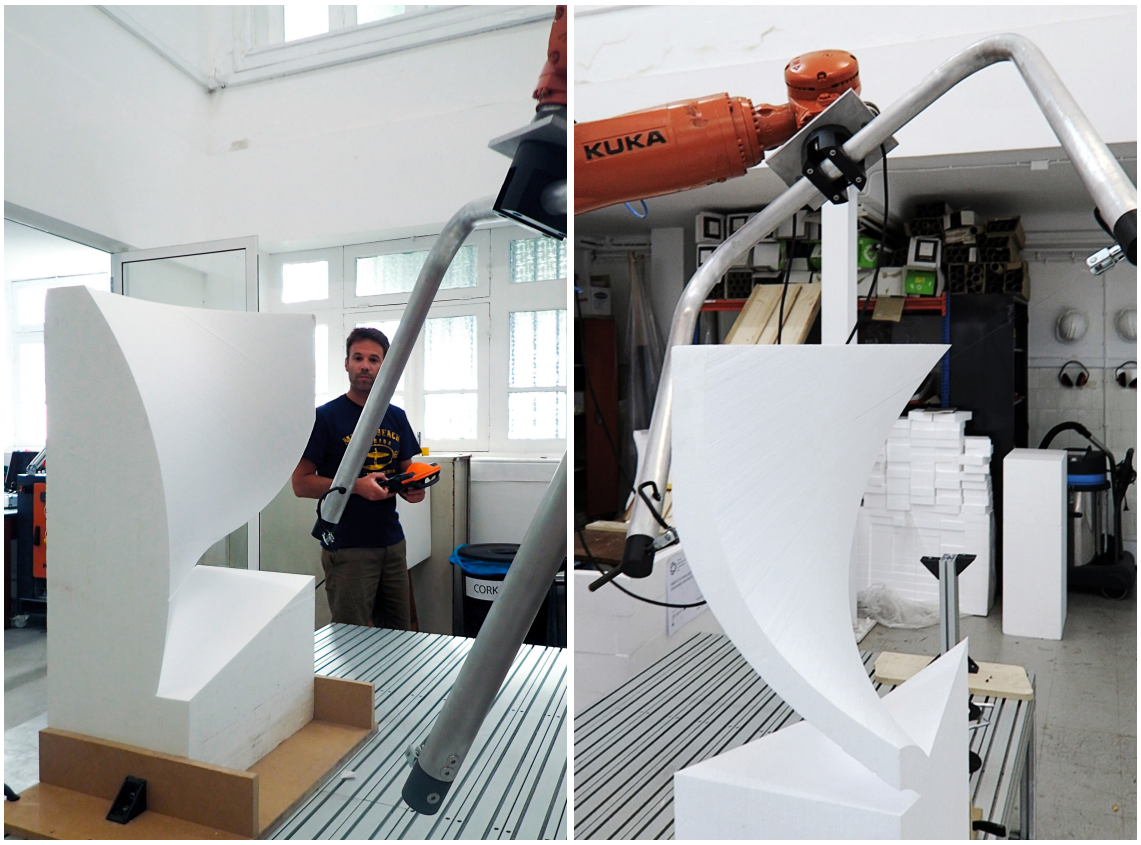


Figure 4.48: Main cutting operations for MSE panels: a) front surface exposed after cutting; b) back surface after cutting, during core perimeter cut.

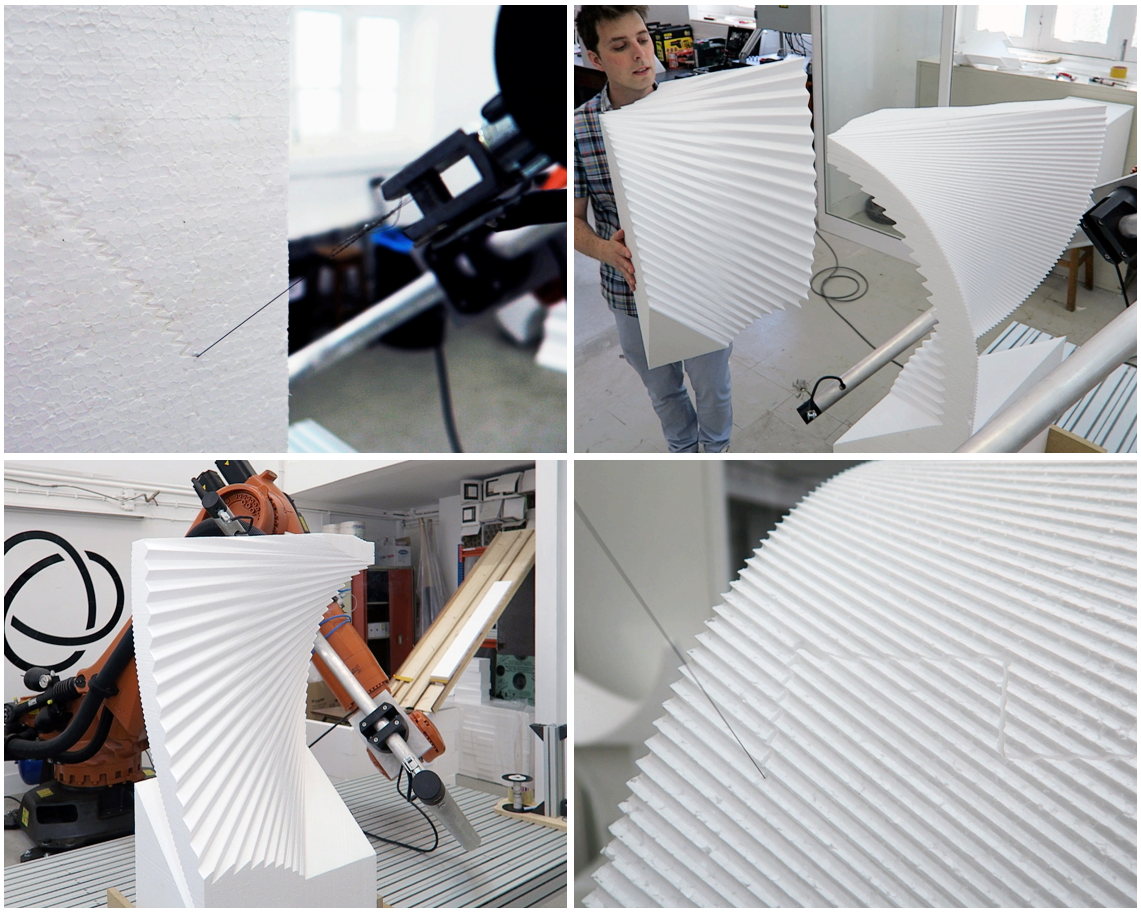


Figure 4.49: Main cutting operations for textured panel 2: a) detail of the kerf size in the first surface cut; b) second cut and removal of excess part; c) beginning of perimeter cut; d) detail of kerf size in perimeter cut.

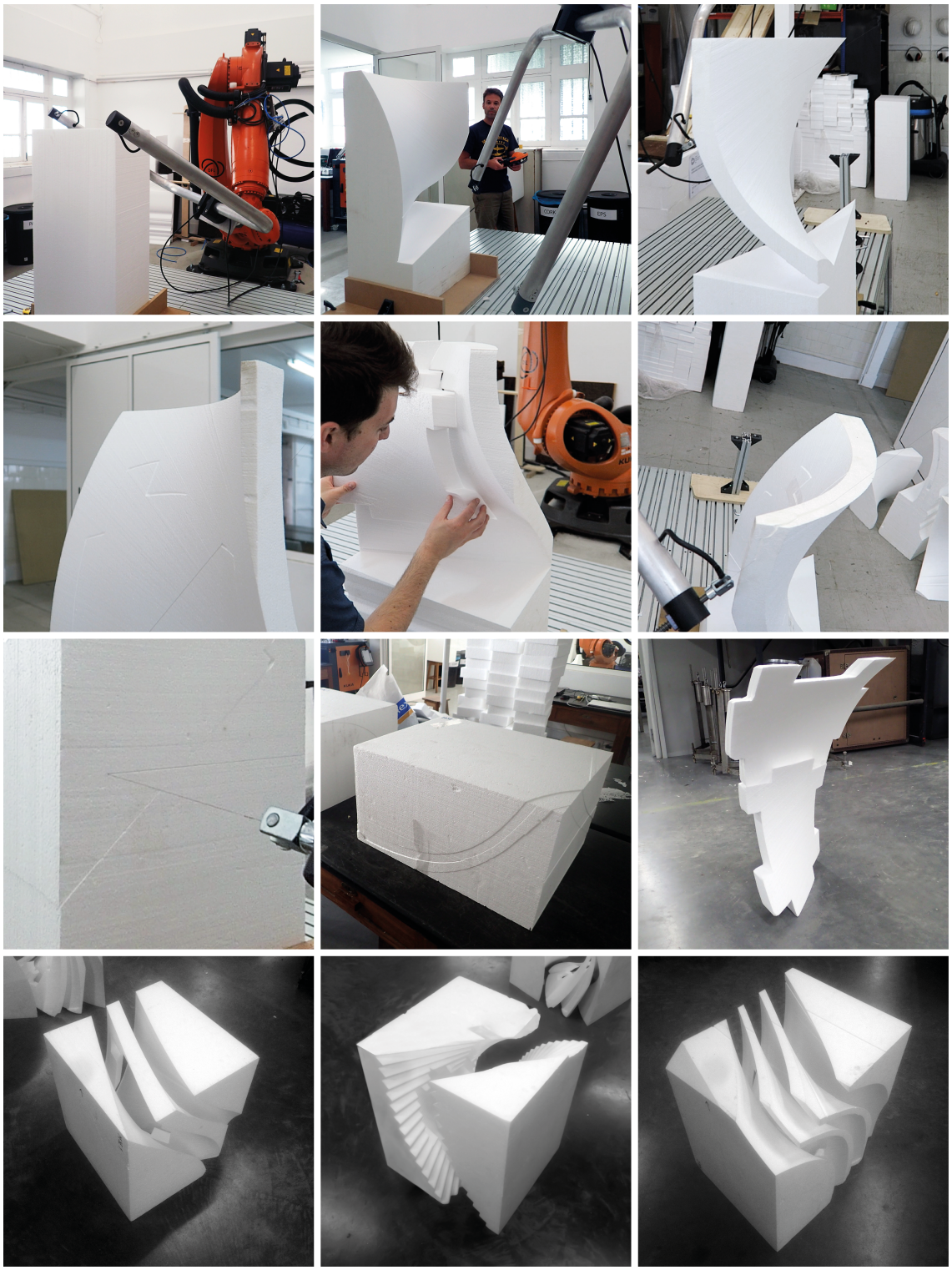


Figure 4.50: Mould cutting for the MSE panel 4 and finished parts: a) Stock check; b) front face cutting pass; c) back face cutting pass; d) perimeter core cut; e) core reassembly; f) core thickness cut; g) horizontal undercut after re-assembly; h) mould volume completed and assembled; i) surface continuity check, using core parts; j) parts for panel 1; k) parts for panel 2; l) parts for panel 4.

4.3.5 Materials and casting

Regarding the materialization of complex geometries in concrete, one critical aspect of making these processes viable is the design of the concrete mix. The same reasons concerning geometric complexity that frequently justify the use of digital fabrication technologies for concrete production, often require custom concrete compositions to become viable.

In the case of this experiment, the curved geometry of the panels, their relatively small thickness and the mould geometry necessary, created a difficult accessibility inside the mould cavities. Thus, two main issues were considered that defined the concrete mix used: the necessity of reinforcement and the need for an adequate flow of concrete while casting.

Because of the curved geometry, traditional reinforcement strategies using metal rods would not be possible to achieve in practical terms. Moreover, although the panels were not designed as structural construction elements, a reinforcement solution was still deemed necessary for self-supporting of the finished panels.

On the other hand, because of the same issues, the concrete mix needed an adequate flow in its fresh state in order to correctly fill the relatively thin cavities of the moulds. Regular concrete mixes, which have high viscosity from the use of large aggregates and low water ratios, would most likely become either wedged between reinforcement and the mould walls or would simply not flow inside the mould[4]. This issue would be compounded by the difficulty of directly vibrating the interior of the mould, due to the curved geometry.

Considering these issues, the concrete used was a self-compacting, fibre reinforced concrete mix, containing cement, limestone filler and very small aggregates. A super plasticizer additive was also included to increase the workability of the concrete in its wet state, without increasing the water ration which would in turn decrease the overall strength of the concrete. Reinforcement in was created through the use of polypropylene fibres which were added in the mixing process.

Both mixes used, mix A for panels 1 and 2 and mix B for panel 4, differed only in the pigments used. For the third panel, the mix used contained grey portland cement and fly ashes as a dark pigment. Mix compositions for both cases are presented in Figure 4.51 and the mixing process illustrated in Figure 4.52.

Although the material variability in this exercise was purely aesthetic, other performative changes

[4] Although workability in wet concrete could be improved by simply increasing the water content, this would result in a concrete mix with an unadequate mechanical strength.

Mix 1 - Materials	Quantities (kg/m3)
Cement (CEM II/B -L 32,5 R (B r))	630,6
Limestone filler	283,8
Fine sand	622,7
Medium Sand	622,7
Water	198,6
Super plasticizer (Viscocrete 3005)	6,0
Fibres - Meyco Fib SP 630 (BASF)	6,0

Mix 2 - Materials	Quantities (kg/m3)
Cement (CEM I 42,5 R)	630,6
Fly ashes	244,4
Fine Sand	622,7
Medium Sand	622,7
Water	198,6
Super plasticizer (Viscocrete 3006)	16,0
Fibres Meyco Fib SP 630 (BASF)	6,0

Figure 4.51: Mix compositions for MSE panels. a) panels 1 and 2; b) panel 4

could be explored in the same manner. For example, changes in weight, mechanical resistance, thermal or acoustical behaviour could be achieved with the introduction of different material elements in the concrete matrix.[5]



Figure 4.52: Mixing process. a) mix with all components before addition of superplasticizer; b) mix with superplasticizer and polypropylene fibres; c) finished mix before casting.

For the casting process, the moulds were treated with a demoulding agent and a lateral bracing was applied to ensure no buckling would occur (Figure 4.53 d)). A conscious decision was made to avoid the use of time-consuming coating applications, as was observed in earlier examples. It was our understanding that it would defeat the purpose of developing a time efficient process for formwork creation. Furthermore, it was an opportunity to study the textural quality of concrete, emerging from this process.

Panels 1 and 2 were cast and set for 60 hours, before demoulding (Figure 4.53 g,h,i). In the case of panel 3, we followed an iterative process for the casting of the two layers of concrete. An initial cast of the first layer, with mix A, followed by a 24 hours of curing and a partial demoulding, opening of the second interior void and re bracing the mould. The casting of the second layer with mix B followed and the final demoulding was done after 72 hours.

[5]Preliminary experiments were conducted with custom concrete mixes that incorporated EPS granules, for weight reduction.Adequate results were not achieved due to the difficulty of maintaining material homogeneity in the concrete matrix.

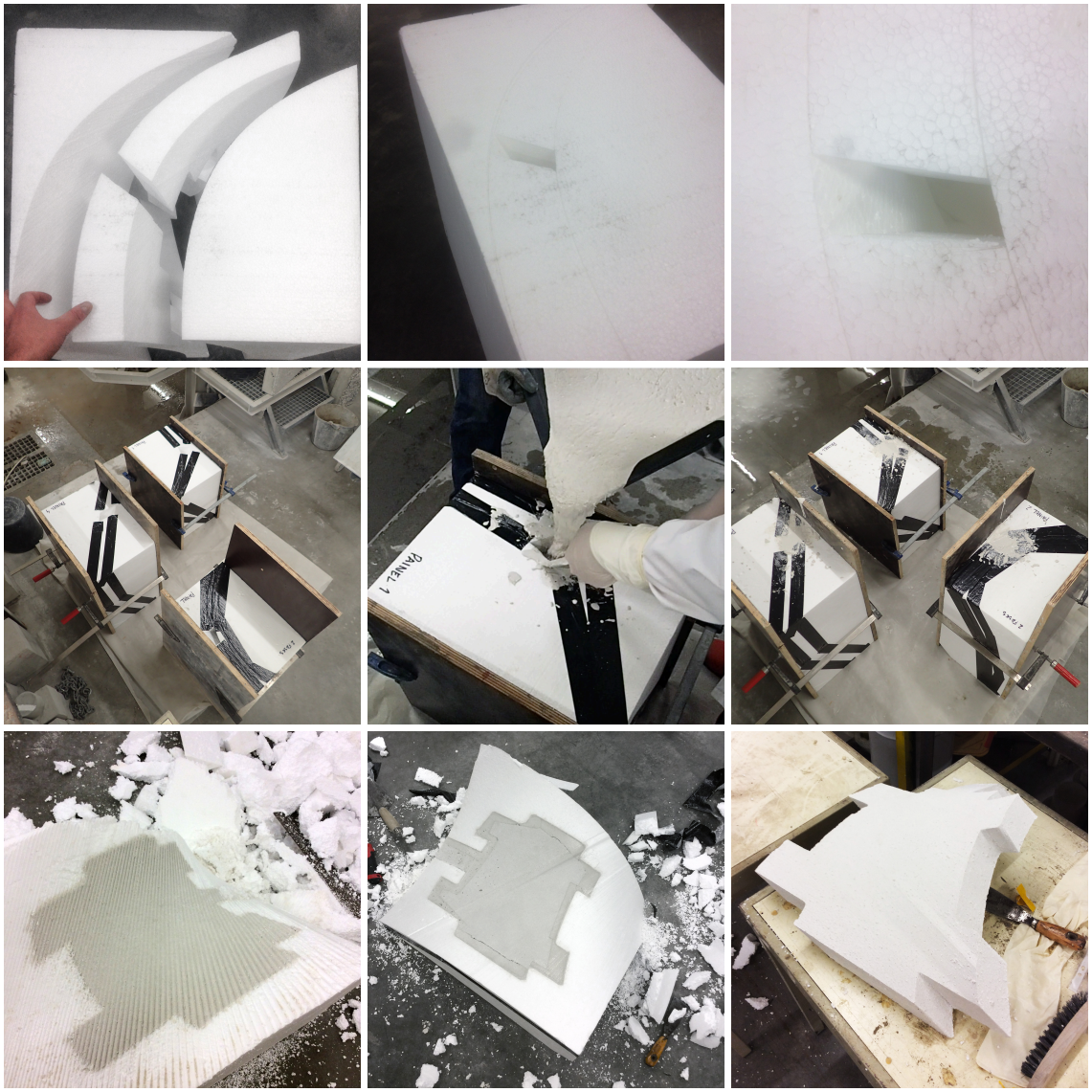


Figure 4.53: Mould preparation, casting and demoulding of the MSE panels: (left to right, top to bottom) a) mould parts for panel 1 before preparation; mould parts assembled after demoulding oil coating; c) detail of casting channel; d) moulds after bracing; e) casting procedure for panel 1; f) moulds after casting; g) demoulding of first surface for panel 2; h) demoulding of first surface for panel 1; i) panel 1 with protruding casting channel after demoulding.

4.3.6 Results

After casting and demoulding, the casting channel positive sections were cut, using a grinder disk and the MSE panels were assembled as presented in the following images (Figure 4.54, Figure 4.55, Figure 4.56).



Figure 4.54: Assembly of panels 1 and 4.

Considering the objectives defined for this experimental prototype: exploring form, surface effects and methodologies for non-homogenous concrete compositions, we develop the following

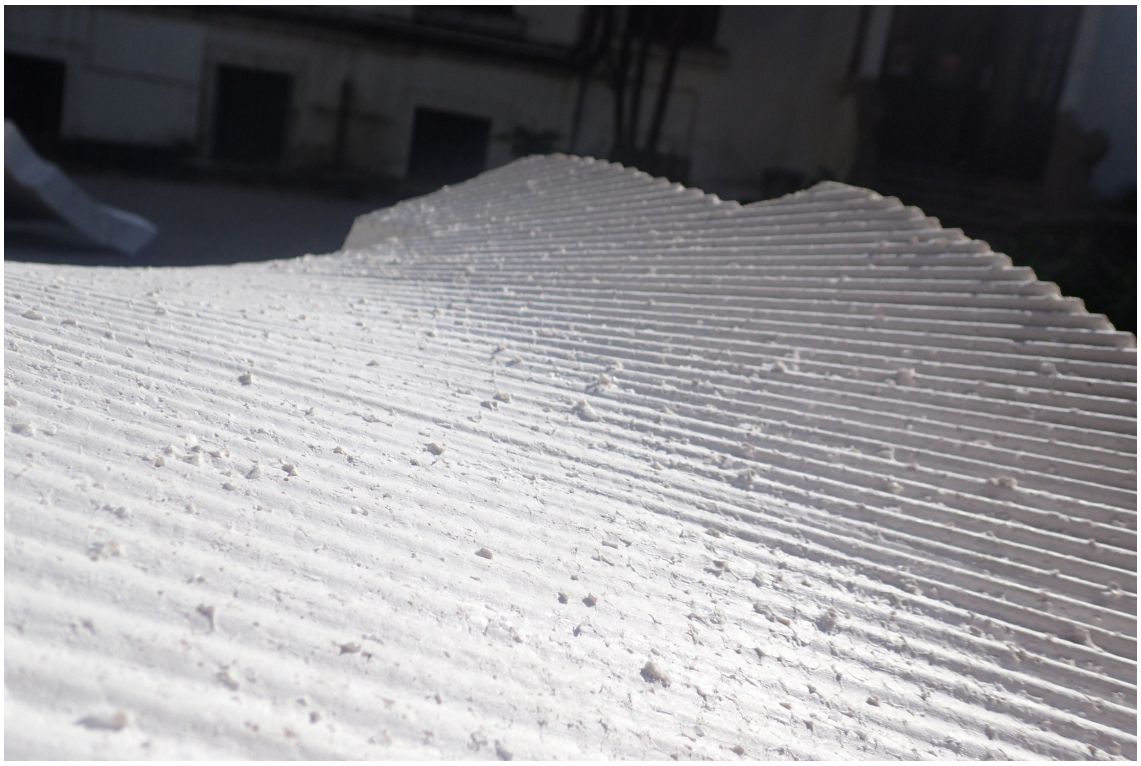


Figure 4.55: Surface detail for textured panel 2.

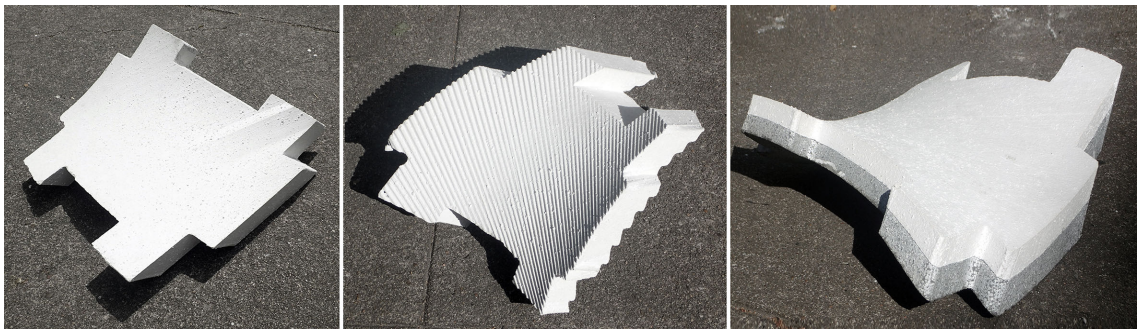


Figure 4.56: Finished MSE panels.

conclusions.

Form and geometric difficulties.

The overall formal challenges were overcome, with the general high curvature radius of the surfaces not presenting significant issues to the digital fabrication process. This included the overall front and back surfaces, as well as the perimeter cuts, with sharp corners being cut with minimal rounding, resulting from the tool path subdivision settings used, which didn't take into account these points. Some unevenness in edges of the concrete elements was attributed to the extreme distortion of the panel geometry in these places, which resulted in very sharp edges which cracked with greater ease (Figure 4.57).

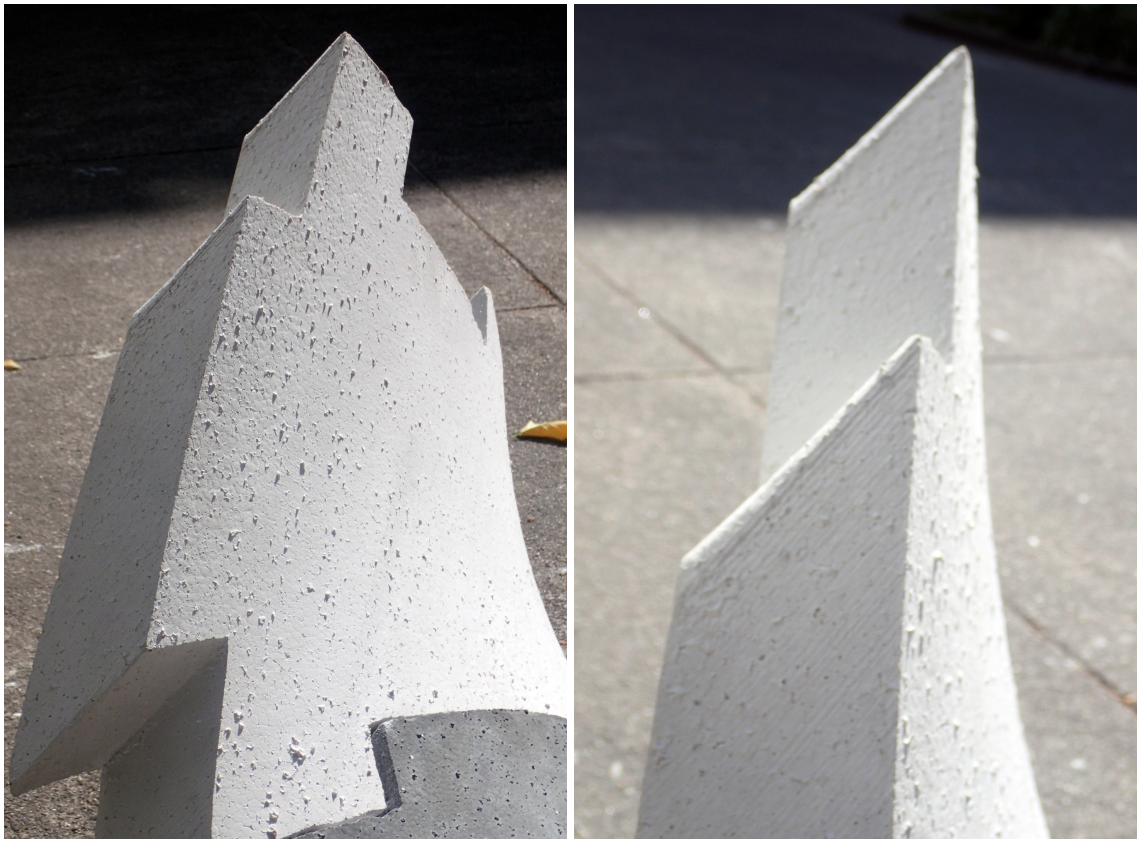


Figure 4.57: Details of the edges of panel 1.

Regarding the geometrical features of the MSE panels, the only issue arising was related with size. Considering that the size of uncut EPS blocks does not prevent the scaling of this technology to construction-scale elements, the major size constraint was clearly in the available length

of the hot wire. As mentioned in subsection 4.2.5 - Practical issues of RHWC, there is a size limit to RHWC fabricated moulds without assembling smaller parts. This depends on the size of the RHWC tool and the available length of the cutting wire, which in our setup, defined a maximum cutting length of approximately 85 cm in the direction of the ruling lines.

Although the fabricated components were not extraordinarily large, with largest dimensions of approximately 50 cm, because the borders of the proposed elements were not parallel with the ruling lines, the hot wire described a diagonal movement through the blocks. This meant that the seemingly adequate length of the 85 cm wire was used in all its extension for the production of the otherwise relatively small components. As such, the final size of the component is not as critical as its size in the ruling direction of the surface to determine maximum dimensions.

Optimization and the closed moulds

A usual solution to the problem of optimizing material usage when producing multiple components from large stock material, such as EPS blocks, is positioning and rotating the desired elements using nesting algorithms which minimize the volume necessary to carve the desired geometry out of a stock volume.

Nevertheless, depending on the selected casting process, we also found that a balance must be struck with regard to the relevance of determining horizontal faces for concrete pouring. Although the concept of closed moulds was successful in reproducing the complex design geometry, with the added difficulties of custom perimeters, and both panel sides apparent, we concluded that the casting process would have been more efficient if the moulds had featured one open lateral side for the concrete pour. This would have also increased the precision of the process, without the need for defining pouring channels and removing their positive volumes after casting.

Surface Quality

One of the most relevant issues regarding the acceptance of these techniques in the concrete industry is the perceived poor surface quality of the finished elements. In the case of this experiment, we found an evident lack of smoothness in the finished surfaces when compared to concrete cast with traditional steel or plywood formwork. This is an obvious effect of the porosity of the untreated EPS foam which has macroscopic voids that are filled with concrete while

casting and are thus translated to the final surfaces (Figure 4.58). This effect could be minimised through various procedures, such as spray coatings (as seen in the Spencer dock bridge example in Chapter 2), the use of intermediate mediums, such as flexible fibreboards or simply by polishing the finished surfaces.

Nevertheless, most notably in the case of panels 1 and 4, we found that the resulting surface had an acceptable quality, close in roughness to surfaces cast with wood board formwork. The absence of treatments or intermediate mediums in the mould surfaces also revealed an interesting textural pattern of apparent ruling lines in some of the concrete surfaces (Figure 4.58 a)). These resulted from the interpolation settings of the RHWC toolpaths and small vibrations in the hot wire, during the cutting process. Because these only happen in the generatrix direction (the wire), they result in emphasizing this geometric feature of the ruled surfaces, materialised through RHWC. This same feature was further explored in the textured design of panel 2.

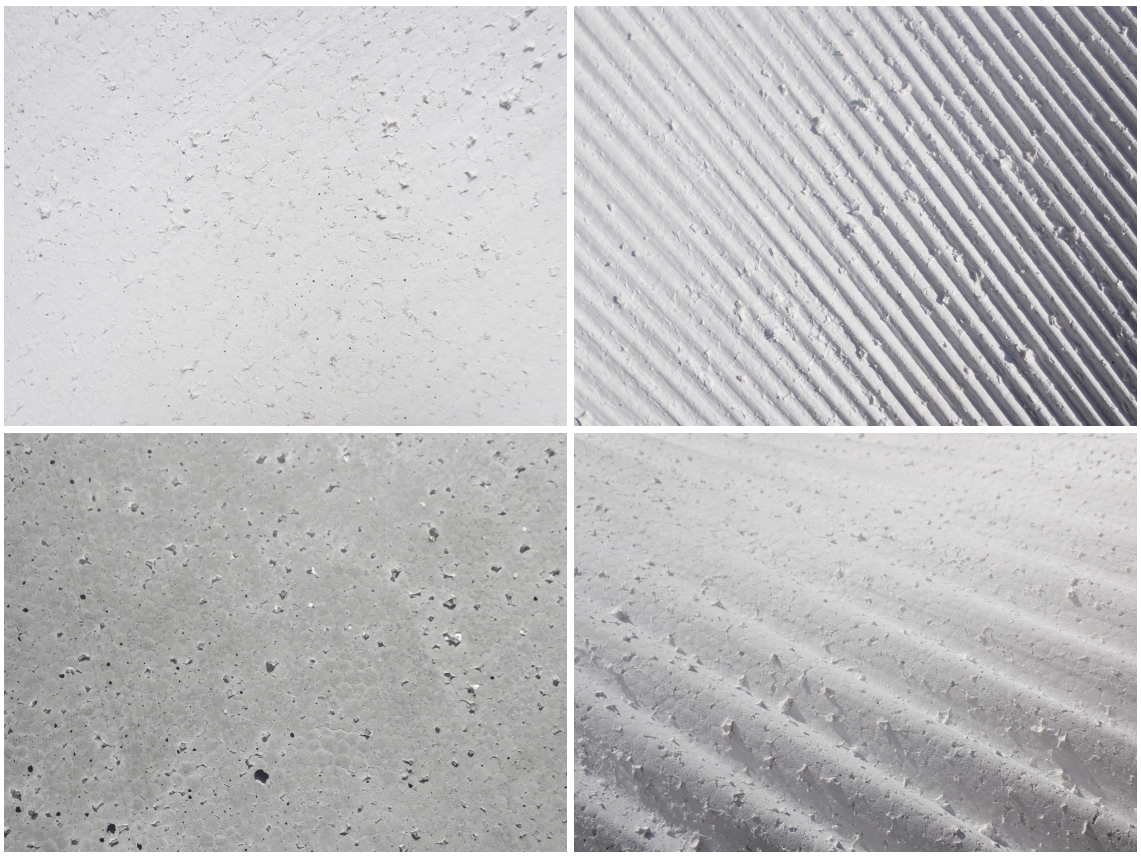


Figure 4.58: Concrete surface textures: a) panel 1 (and panel 3, non-pigmented side) ; b) panel 2, small scale texture; c) panel 3, pigmented side; d) panel 2, large scale texture.

4.4 Revisiting the Philips Pavilion: Layered moulds and material optimization

Mentioned in Chapter 2 - Form (subsection 2.3.1), the Philips Pavilion showcased an interesting approach to the problem of developing concrete formwork solutions that can adapt to complex curved geometries. This connection between ruled geometry, concrete and technology resulted in the particular design features of this work and are the reasons it was selected for the experimental work developed here. In this section, a brief historical background and description is provided to contextualise the following sections.

The Philips Pavilion was designed by Le Corbusier and Iannis Xenaquis for the 1958 World Fair, in Brussels. As the main proposed concept, the pavilion was to be a showcase designed and built around the multimedia installation named Poème Életronique. The design plan developed by Le Corbusier featured a curved, stomach-like plan, with an entrance, a main central space for spectators and an exit (Figure 4.59 a)). This plan was spatially developed by Iannis Xenaquis, using ruled geometry to create a group of curved surfaces of variable radii, with three peaks. These surfaces were the main feature of the design and defined the interior space, projection areas and the overall shape of the pavilion.

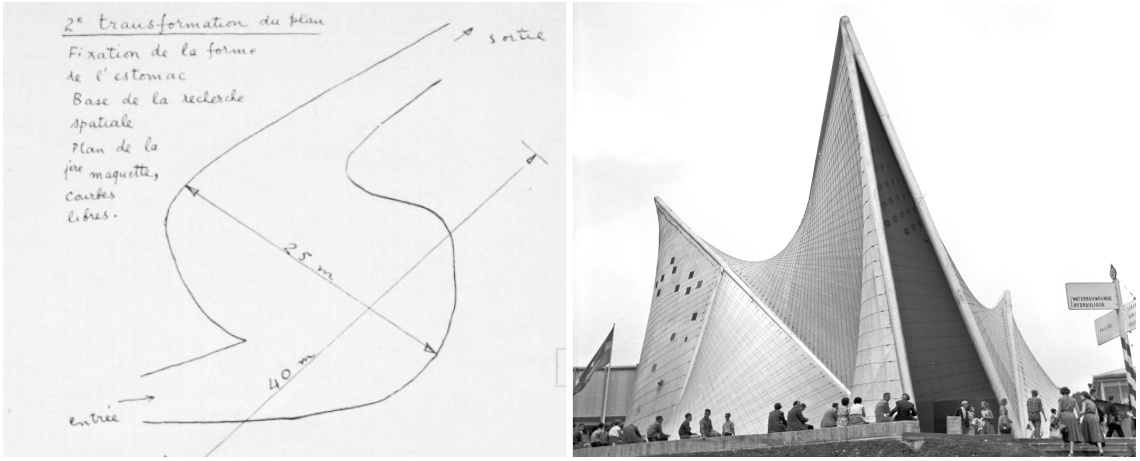


Figure 4.59: a) sketch of general plan by Le Corbusier; b) Philips Pavilion, circa 1959 (Xenakis et al., 1958)

The design of the ruled surfaces that composed the pavilion went through three stages, starting with a combination of cones, conoids and hyperbolic paraboloids. In subsequent designs, the conoids and cones were discarded and the final design was composed exclusively of hyperbolic

paraboloid surfaces. This was done mainly to ensure a more accurate description of the curved surfaces and facilitate the calculation of their static stress forces (Xenakis et al., 1958).

The constructive design of the pavilion also went through several instances and different material proposals, from metallic skeletal structures with metal reinforced surfaces, to double walled concrete shells. The final solution used a pre-stressed concrete "skeletal" structure along the ruled surface edges. The surface areas were built with precast concrete panels, with a 5cm thickness, which after being set in the correct places were mortared and the whole system acted as a pure compression structure.

At the time, their construction was only made possible through an unconventional building process. To achieve the desired surface geometry using precasting, builders subdivided each hypar surface in large sections and recreated them on site, using hand-made sand mounds. These were further subdivided along ruling lines with wood boards, creating a matrix of mould cavities which where then cast with concrete and a small reinforcement mesh for transportation purposes. Approximately 2000 rhomboid concrete panels composing the 9 concrete surfaces of the pavilion were precast, moved onto a scaffold structure and mortared, creating the final exterior ruled surfaces of the pavilion (Xenakis et al., 1958) (Figure 4.60).

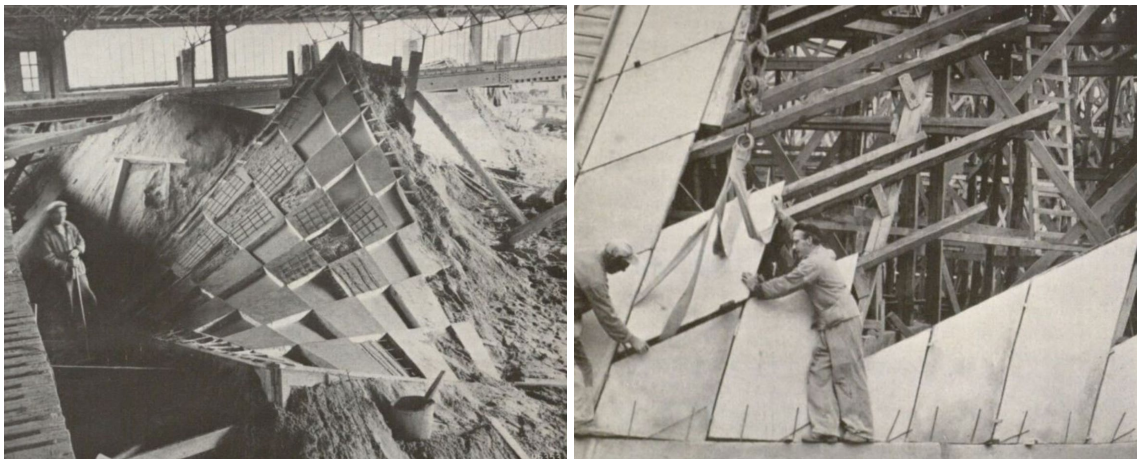


Figure 4.60: Philips Pavilion construction method. a) sand formwork system for precast panels; b) finished precast panels after installation on site ((Xenakis et al., 1958)).

These precast panels that defined the hypar surfaces of the pavilion are the main feature of interest in the scope of this thesis as RHWC could be tested as an alternative solution to this task.

Although ultimately successful, it was an expensive and labor intensive process, imparting specific design constraints on the architecture of the Philips Pavilion, mainly related with the ne-

cessity of following ruling lines in the precast panel geometry.

While there has been some research pointing to strategies for rebuilding the Philips Pavilion using modern construction technologies, it generally dismisses the original prefabricated subdivision strategy that gave it its character, for more efficient construction strategies. Methods such as in-situ concreting, large prefabricated shells and sprayed concrete using membrane formworks can be found in existing literature (Pronk et al., 2007); (Nijse, 2008).

Although as of yet there hasn't been an actual reconstruction of the pavilion, these demonstrate not only the continuing architectural relevance of the Philips Pavilion but also the non-trivial challenge that erecting such a structure still presents today.

4.4.1 Objectives

Building on the previous experiments, characterising the RHWC process, defining a basic mould system and complete procedures for precasting concrete parts, this third experiment takes this knowledge further and intends to explore the increased the sustainability of the RHWC formwork fabrication process. This is developed by expanding the previously defined strategy of the layered mould and optimizing material expenditures, consequently reducing waste generation.

This experiment proposes to address these issues by rethinking the design and precasting system of the seminal work of Jannis Xenaquis and Le Corbusier, the Philips Pavilion, with RHWC fabrication and layered moulds in mind. Considering the ruled geometry of the pavilion and the original precast strategy, we believe that RHWC can not only improve the efficiency and sustainability of the construction process, but can also introduce new possibilities in the design of the pavilion. All the while, maintaining a tectonic link between construction and design already present in the original work.

In this background, this section explores a new method for the construction of the Philips Pavilion, using RHWC, focusing on 2 main goals:

- Develop an optimized layered formwork system, based on the sequential cutting of large Expanded Polystyrene (EPS) blocks, optimizing material usage and production processes, while maintaining its economical and industrial viability.
- Define and explore a new design space for the pavilions' panel geometry, emerging from the properties of this digital fabrication process and the geometrical needs of the mould

strategy, stepping forward from the original construction related geometrical constraints.

4.4.2 Recreating the Philips Pavilion Geometry

To develop this study, a digital base model of the Philips Pavilion was created in Rhinoceros 3D. This model was based on the information available in (Xenakis et al., 1958), particularly, the descriptions and plan drawings of the pavilion, with projections of all structural edge lines and hight measures of the vertex points of the structure.

According to literature and available drawings, the final design was composed of 9 hypar surfaces, identified in the general plan as (PH) A, B, C, D, E, F, G, K and M. Hypars A, B, C, D, E and F intersected the ground level, defining the curved plan and hypars G, K and M where fully suspended, leaving 2 triangular openings as entry and exit portals. The three peaks sat at 20.5m, 13m and 18.5m above ground (Figure 4.61 a)).

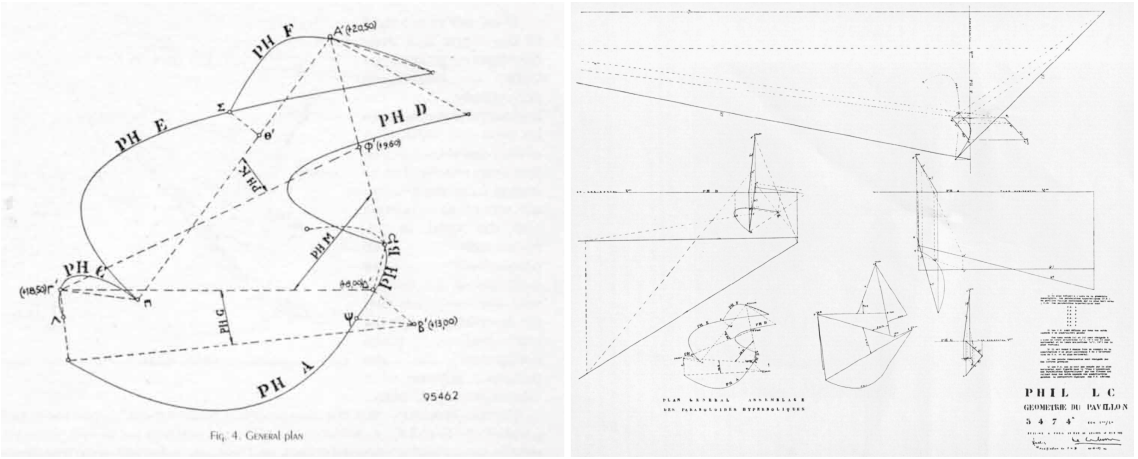


Figure 4.61: Philps pavilion original drawings: a) general plan of the final design with peak hights; b) 1:200 scale drawings of part of the wall surfaces of the final design. (Xenakis et al., 1958)

With this information, an initial model was built by recreating this available geometry in Rhinoceros 3D. This process was straightforward for hypars G,K and M, with available boundary segments that could be swept, recreating the doubly ruled hyperbolic paraboloid surfaces. Hypars A, B, C, D, E and F which intersected the ground level could not be recreated in the same fashion as sweeping the ground curve and the top edges does not result in a hyperbolic paraboloid surface and available projection drawings of these surfaces[6] were not of practical use (Figure 4.61 b)).

[6] These drawings contain the projections of opposing generatrices used in the original surface designs. In most cases, the top one is a part of the structure and the bottom one sits below the ground level.

This aspect was considered very relevant as its double ruled property was the main feature of the original pavilion.

Therefore, to create a more accurate 3D model of all the surfaces, a different strategy was employed that digitally recreated the manual process originally used for the design of the ruled surfaces. This process worked by defining a hypar surface in space with two straight line segments (directrices) and equally spaced rulings between them. This wire surface was then moved and intersected with a ground plane until a desired plan shape was found.

Our digital version of this strategy started from the base geometry already modelled, composed of the edge lines (corresponding to generatrices of each surface in the original model) and the curved plan lines (the result of the intersection between the desired surface and the ground plane). With these inputs fixed in space, for each of the 6 ground hypar surfaces, a parametric model was created to find the position of the lower generatrix line and recreate a new hypar surface which produced the intersecting plan curve closest to the original curve.

This was achieved with an evolutionary algorithm created in Grasshopper for Rhinoceros, using the single objective solver found in the Galapagos plugin. Using the mentioned fixed elements, each generation would vary in the position of the bottom generatrix, changing the shape of the ground intersection curve. Thus, the fitness function searched for the minimisation of the overall sum of the distance between points in the original curved plan line and the new curved plan line for each generation. After 30-40 generations an adequate hyperbolic paraboloid surfaces could be found with a discrepancy no larger than 5cm to the original line.

Using this methodology, a new complete model of the Philips Pavilion was created which featured a more accurate approximation of the hypar geometry and was used as a basis for further experimentation Figure 4.62.

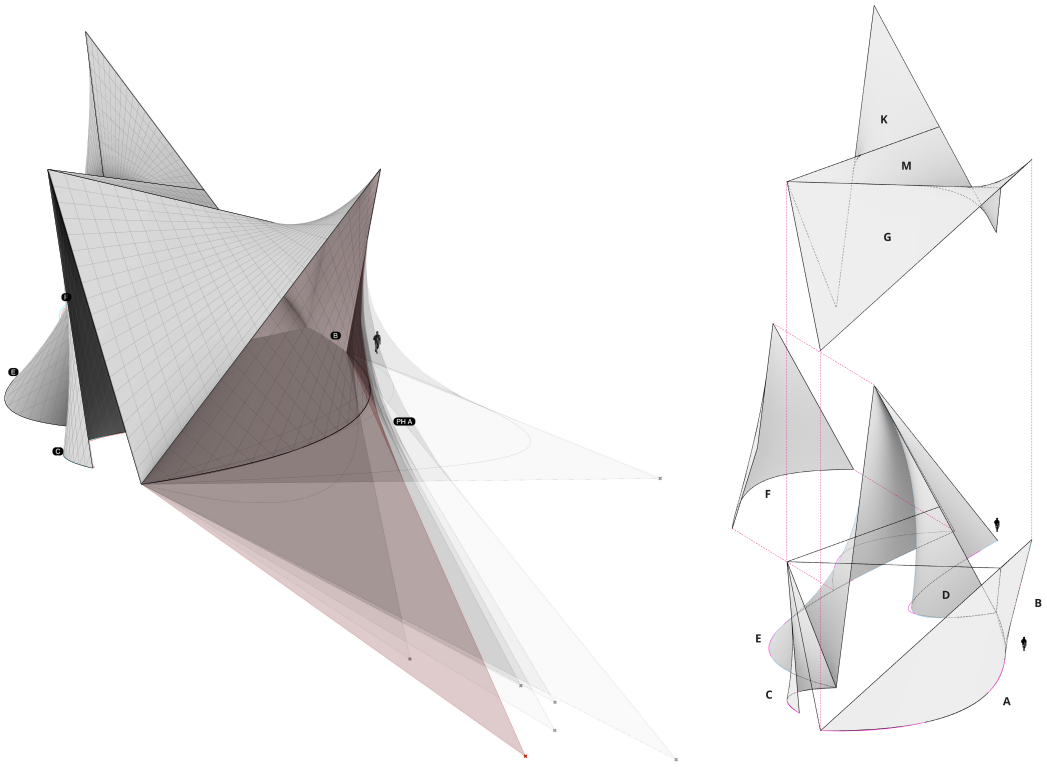


Figure 4.62: Redesigning the geometry of the Philips Pavilion. a) representation of various generations of the form finding process for the definition of the hypar surface A, with final in red (grey lines illustrate the ruling directions found for each hypar surface); b) resulting exploded geometry of the 9 hypar surfaces generated.

4.4.3 An optimized layered mould strategy

To achieve the stated objectives of rematerializing the surfaces of the Philips Pavilion using RHWC, a new mould design was developed, focusing on fully leveraging the slicing logic of this technology to optimize material usage in the required formwork and explore its architectural consequences.

In the layered mould design adopted in the previous experiment, although the RWHC process allowed for the easy creation of successive mould surfaces, all such cuts were used for the same mould. Thus, in a sense, it followed a traditional logic for precasting concrete elements, as its usage was similar to other precast mould strategies - one mould per cast part.

Maintaining the objective of producing precast lightweight concrete panels, an extension to the slicing logic and the layered mould previously described, would be to simply create multiple slices from one stock volume in such a way that the parts of each slice could be separated and the resulting voids, cast (Figure 4.63). This would result in a set of stacked surfaces that could all be cut and cast in sequence.

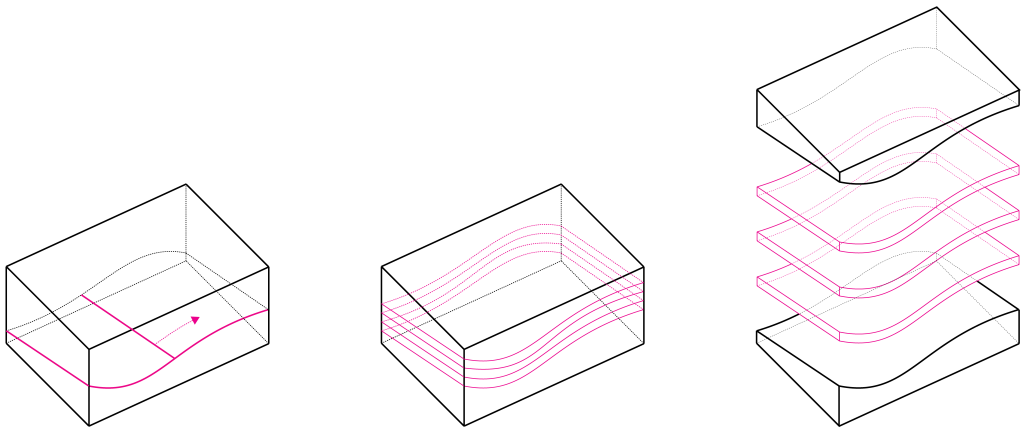


Figure 4.63: Sequential slicing and stacking of ruled surfaces for casting voids.

This logic of stacked moulds for concrete production, is not an entirely new one. In academia, there have been examples of the use of similar strategies, applied to concrete, using different fabrication processes (Enrique, Lluis and Schwartz, Joseph, 2016) or directly to other materials such as ceramics (Bard et al., 2012). In the precast industry there is also the specific precedent

of mould batteries for the large scale production of identical flat, double-sided concrete panels Figure 4.64. The central aspect of this logic in all cases is that elements can be cast (or cut) side by side, with one side of one element being coincident with another side of the next or with an intermediate element between.

In all such examples, because of this feature of placing different surfaces side-by-side, geometric concessions have to be made. On the front-back surfaces, either all panels are flat (mould batteries) or the bottom side of one is the same as the top side of the next. On the lateral faces, all panels tend to have the same surface direction.

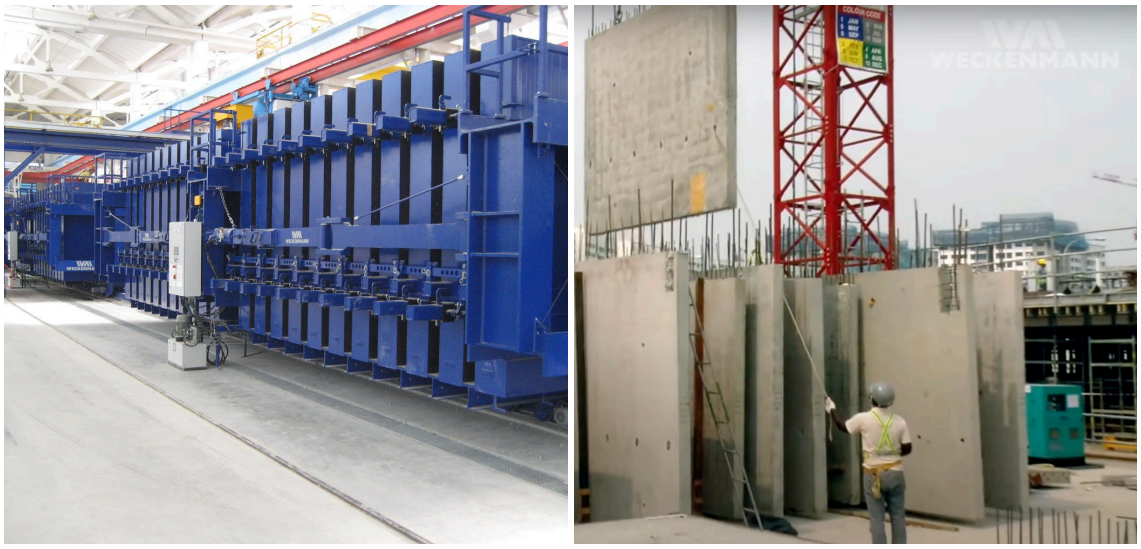


Figure 4.64: Weckenmann battery mould for precasting of flat concrete wall or slab elements.

This sequential slicing and stacking logic is, in effect, a simplification and optimisation of the layered logic defined in the previous experiment. In this case, a stacked mould can be created from one single EPS block that is sequentially cut. Towards this objective, the position of the panel geometry inside the stock volume is fundamental. Depending on the shape geometry and the positioning of a panel surface within the stock material, different conditions can be created. For instance, if the minimization of the stock volume is the main point, this can be achieved, but either the stock volume is cut to fit the panel or all panel sides are inside the volume. If the intended goal is the minization of cuts, for certain panel geometries, the panel can be repositioned inside the stock such as all sides are coincident with the exterior faces of a parallelepipedic stock volume. In this situation, such a panel can be cut in a single pass, resulting in the desired design surface. Figure 4.65 illustrates three different possible positions for one rhomboid panel inside a parallelepipedic stock volume.

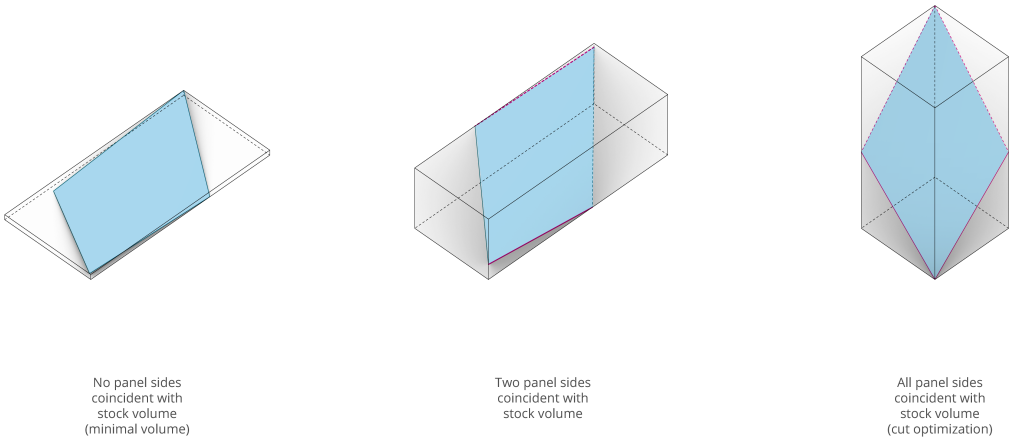


Figure 4.65: Different possibilities of nesting the same surface patch inside a stock volume, considering different objectives: a)minimising hight (no sides coincident) b) 2 sides coincident with volume faces;; c) 4 sides coincident with volume faces.

If this final condition is met (all edges coincident), the resulting mould parts can simply be separated leaving voids to be cast with concrete. We call one such set of cutting surfaces grouped into one stock volume, a stack. The number and dimensions of such stacks can vary according to the needed element size and available dimensions of stock EPS.

This optimized process has some practical design consequences. First, all panels in the same stack must have the same (projected) perimeter geometry, in case of a regular stock block. Secondly, all panels produced in such a way will have constant thickness, as both front and back faces of each panel are the result of just one cutting surface which is then separated creating a casting void. Thirdly and most importantly, because of the first point, traditional surface panelisation processes for generally curved surfaces, which often produce differently shaped elements, cannot be used as they would imply that each panel would have a specific perimeter part and thus we would be in the same situation as the previous prototype. As such, to maintain this optimisation that pressuposes equal perimeters in projection, particular procedures of surface subdivision have to be used that result in patches which can be oriented inside a stock volume with coincident perimeter shapes in the vertical direction.

A final relevant issue is that because the act of separating mould parts creates the actual thickness of the desired panels and all separations are made along the stack z direction, all panels have their third dimension along the same direction when in their final position.

Figure 4.66 illustrates the general mold design and envisioned procedures for the optimized stacked mold strategy: Sequential cutting of a stock volume; separating the mold parts with the desired distance according to the panel thickness; casting the resulting void spaces.

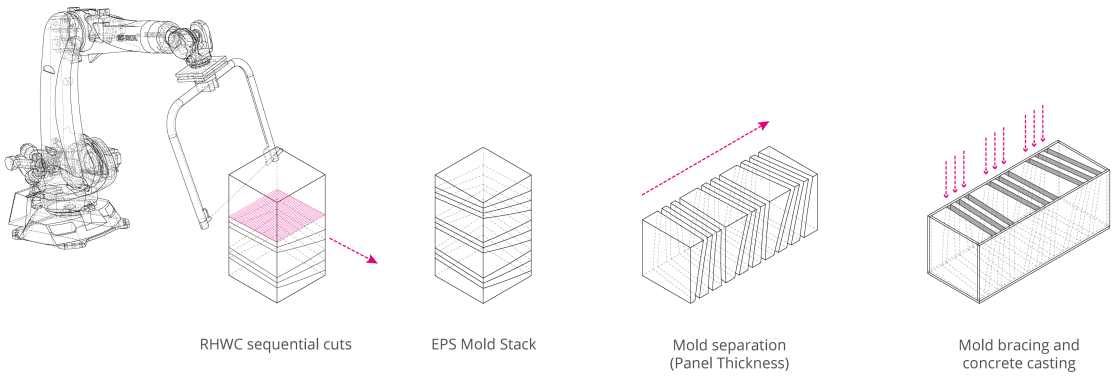


Figure 4.66: General stacked mould logic. a) sequential slicing; b) finished mould stack; c) mould separation and void creation; d) bracing and casting.

4.4.4 The geometry of stacked panels

As can be understood from the description of the formwork process used in the construction of the Philips Pavilion, the original panel design for the precast panels was constrained by the necessity of having panel boundaries following the ruling directions of the overall ruled surface. This was imperative for workers to have straight guides for the manual description of the ruled panel surfaces.

In this stacked mould strategy this is no longer the case. Here, the relevant geometrical constrain is the ability to stack the panel surfaces and their relation with the stock geometry. The main issue is that independently of the actual geometry and position of each panel in 3D space, for a set to be stacked, all the panels of the stack must be able to be rotated and nested inside the stock volume in such a way that all panel sides are coincident with faces of this stock volume.

This feature, immediately raises two points of possible interaction: a) the actual shape and size of the stock volume and b) the shape of the panels.

Regarding the issue of the stock volume, to simplify our process, only parallelepipedic geometries were considered at this time. Envisioning the material process ahead, this allowed for easier

fabrication, handling and casting.

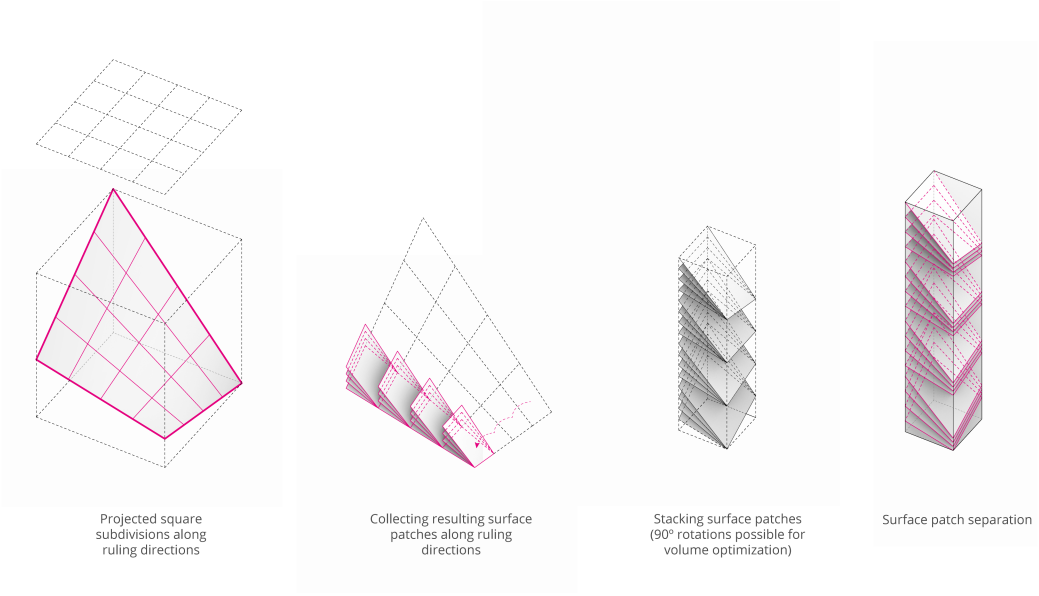


Figure 4.67: Creating stackable panels from square hypar patches through square subdivisions. (Panel reorientations into stack geometry is easy to accomplish by simple orthogonal translations as the panel perimeters form squares in a top view).

The issue of the actual panel shapes relates to the definition of a new surface subdivision strategy which can yield panels with the necessary geometry for stacking. Initial empirical tests led us to experiment with square subdivisions of square hypar patches[7] (Figure 4.67). In this simplified case, the surfaces can be subdivided along both straight ruling directions at regular intervals, resulting in square or rectangular patches. In these cases, it is easy to visualize that if the subdivision is regular along each straight ruling direction, we can manually stack one side of a panel onto the side of the next panel which will be coincident in projection. Thus they can be stacked into one parallelepipedic volume with the same base shape and dimensions as the projected panel geometry. This projected panel geometry becomes the basis for any surface subdivision which can be stacked.

Although these initial tests were simplified to work in the ruling directions, it is evident that the relation between the orientation of the sides of the panel and the actual ruling directions of the surface itself can vary, meaning that other orientations will yield panels with sides not coincident with any ruling direction and therefore, curved along the edges. Moreover, the projection direction (which in this case was vertical) influences the actual size of the resulting panels and

[7] A hyperbolic paraboloid surface patch with both ruling directions parallel to adjacent faces of a cube.

their position in the stacks, meaning that this solution will be most effective when the surface normal direction does not vary much from this projection direction

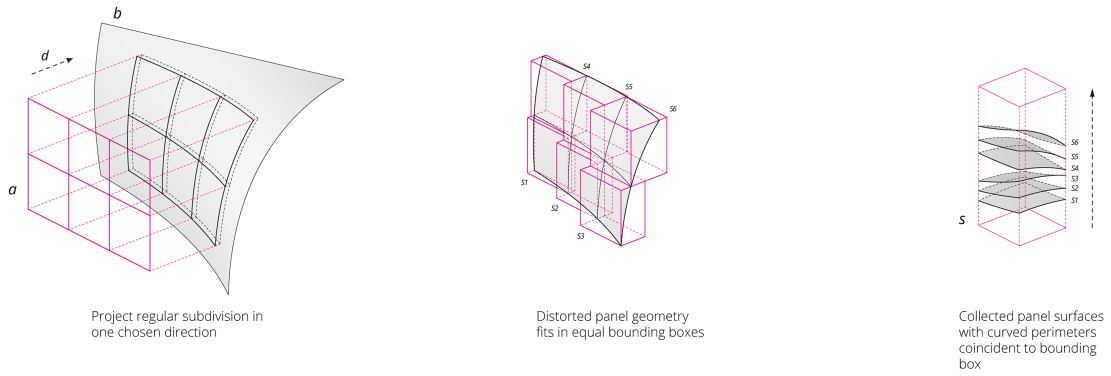


Figure 4.68: General geometrical process for creating stackable surface subdivisions.

From these initial tests, a general geometrical process was developed for achieving viable paneling solutions. This was achieved through the projection of a regular tessellation (a) onto a ruled surface (b), in a direction (d). From this subdivision, created from one projection direction and one regular repeated shape, it it possible to collect all panels and reorganize them vertically along the same direction, resulting in stackable panels. The regular shape of the tessellation dictates the necessary stack section. The projection direction dictates the panel's shape on the surface and its fixed position inside the stack, as well as the direction of its side faces. Figure 4.68 illustrates this process which can be summarized in the following points:

1. Projecting the desired surface onto a plane, following direction d;
2. Subdividing the projected surface using a uniform tessellation (a);
3. Reprojecting the subdivision into the original surface following direction (d);
4. Cutting the surface using the projected subdivision, resulting in panel surfaces;
5. Collecting and stacking the resulting surface patches into stacks by maintaining the orientation of their bounding boxes, creating stack the final stack of oriented surfaces (S).

4.4.5 Tesselation tests

At this stage, the research focused on studying the specific geometry of the surfaces of the Philips pavilion and, using the method previously explained, exploring different hypothesis for surface

panelisations with the goal of understanding their effects on the proposed mould making strategy. These panelling explorations were envisioned for different purposes such as panel size, projected shape geometry (square, rectangular, rhomboid, triangular) and tested different panel edge geometries (straight, along ruling lines or curved). On a design note, considering the original strict subdivision that exacerbated the straight rulings of the hyperbolic paraboloid surface, in these tests, we favoured solutions that produced evidently curved lines.

To explore these subdivision designs and their effects on stacking panels, an algorithm was created that followed the schematic logic in Figure 4.68 of projecting the surface onto a plane, subdividing the resulting flat geometry and re-projecting the divisions back onto the surface. Other more automated surface subdivision and mapping algorithms could have been used but this methodology allowed for more control in the final results. For process simplicity, projection directions were initially defined as perpendiculars to a plane constructed through the union of the three available "vertices" of each hypar. This resulted in manageable panel distortion along the surfaces, for the regular subdivisions tested and allowed for easy relations with the existing panel boundaries.

First tests were conducted using the original logic of subdivisions for hypar A, using both ruling directions. This resulted as expected in rhomboid panels with straight edges, with variable areas and sizes, which nonetheless could be organised into extruded rhomboid stock volumes. Another set of experiments was developed, aiming at creating a more suitable subdivisions for the triangular shaped hypars that intersected the ground level of the pavilion. This used a recursive subdivision logic (connecting the midpoint of each side) resulting in a triangular subdivision of the projected hypar area, with lines paralel to the three sides of the projected surface. Because creating triangular stock volumes was not considered optimal, these directions were explored in different combinations of two, to test different solutions such as horizontal strips, vertical strips and rhomboid panels along directions other than the ruling directions tested previously. All tests resulted in feasible panel geometries which could be accommodated with the defined method into mostly extruded rhomboid stock volumes (Figure 4.69).

Any of such examples could be further tailored into more manageable paralelipedic stock volumes, by taking one direction and sectioning the panels perpendicularly along the adjacent direction. This would also create an interesting staggering effect in the panels, as shown in Figure 4.70.

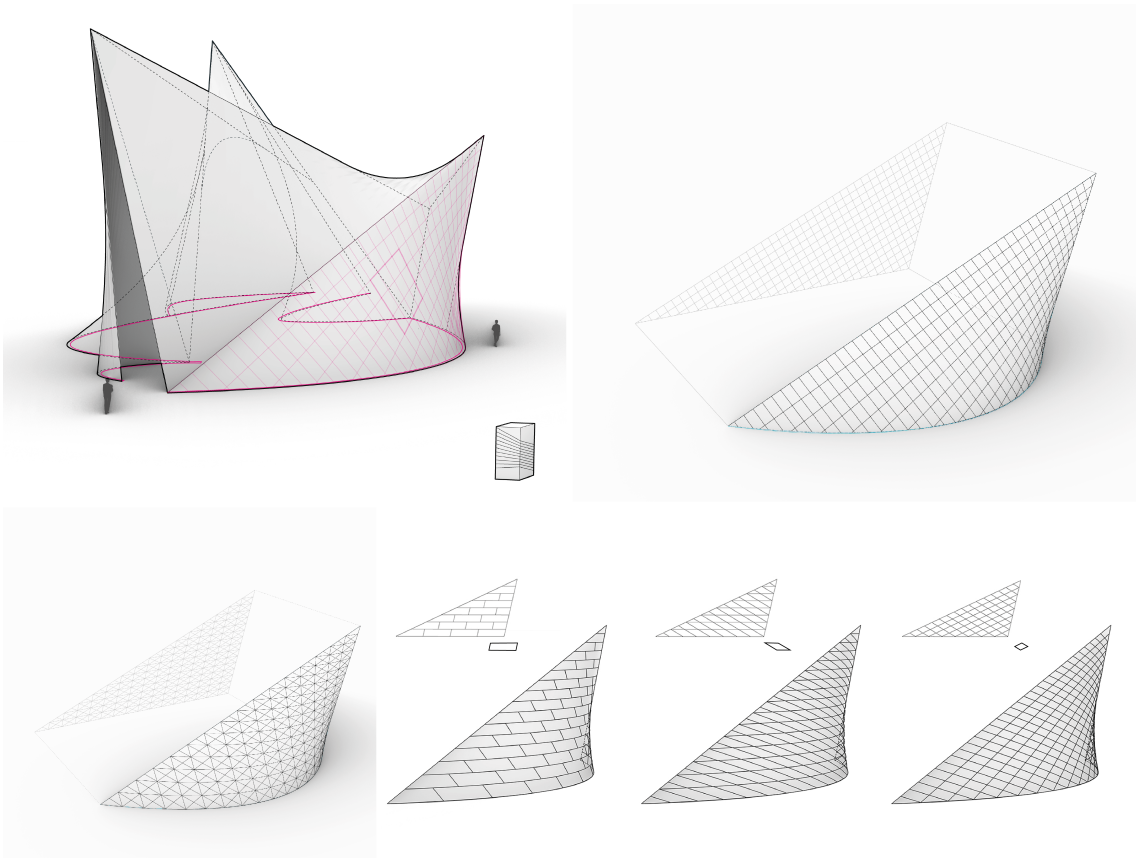


Figure 4.69: Initial surface subdivision tests: a) original subdivision following both ruling directions; b) square subdivision tailored for square projected panels, without following any ruling directions; c) recursive subdivision test, no ruling directions, triangular panels; d), e), f) recursive subdivision grouping 2 directions for quadrilateral panels.

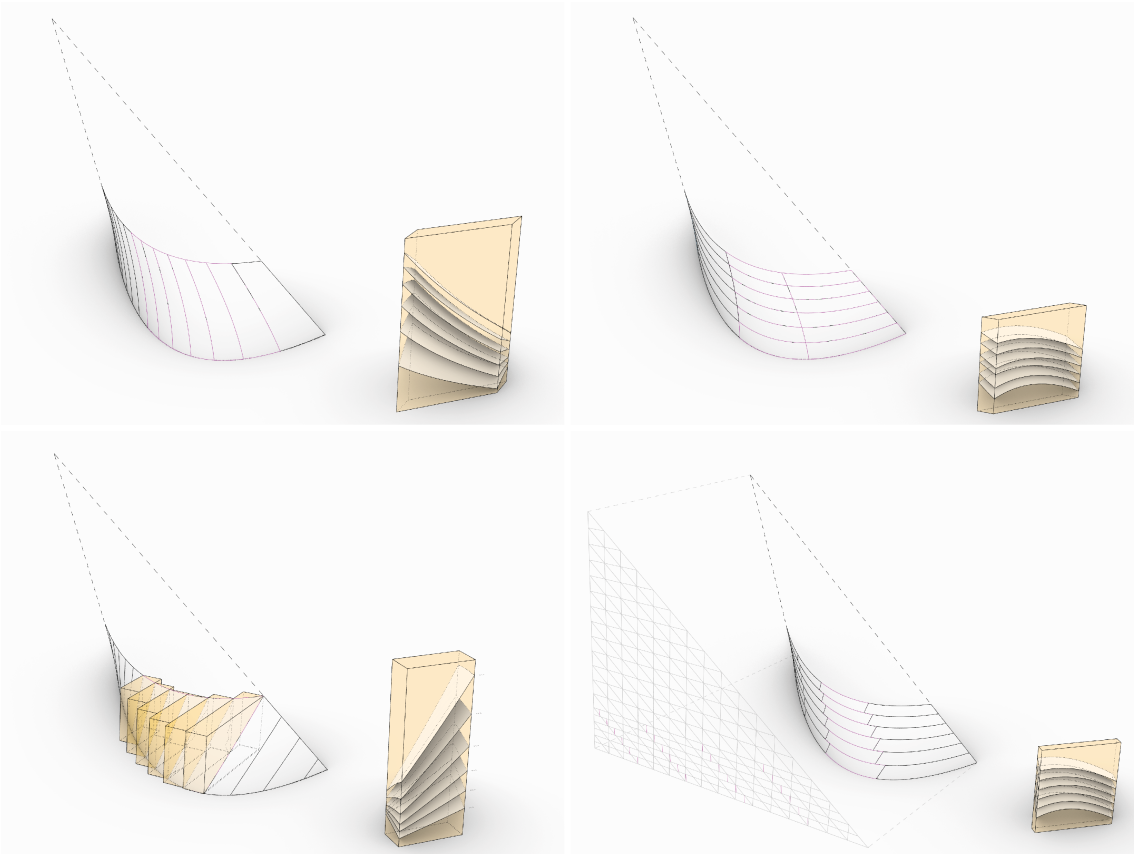


Figure 4.70: Partial stacking tests with PHE and recursive subdivision directions: a), b), c) 2 non ruling directions and resulting rhomboid panels; d) a non-ruling direction + a perpendicular direction, resulting in a parallelepipedic stack

Further testing of the stacking logic was performed in the complete surface of PH A, in order to compare the stacking logic of a complete surface, in a RHWC scenario, with a 3D milling scenario. For this, a strategy was chosen that combined the ease of production of square EPS material blocks with ruled panel edges in one direction and curved edges in another direction. This emphasized the curvature of the ruled surface distinguishing it from the original ruled subdivision (Figure 4.71 a)).

To achieve this subdivision, a projection direction and a corresponding perpendicular projection plane were found so that one of the families of ruling lines of the hypar produced parallel lines when projected. The whole surface was then subdivided into squares of 1 meter by 1 meter, so that the other direction would produce curved panel edges when projected back to the original surface. Furthermore, for this simplified test, boundary panels with irregular geometries, resulting from the specified subdivision strategy, were not taken into account.

Using the Grasshopper plugin for Rhinoceros, an algorithm was developed that automated the

grouping and translation of the resulting 135 individual panels into stacks of 10 panels each. Inside each stack, panels were separated with a minimum distance of 10 cm between panel surfaces. Other optimisations would have been possible, such as grouping panels with similar rotations in the same stack but they were not attempted.

Finally, the described strategy was compared to a scenario of CNC milling for individualized moulds, using the same subdivision geometry. For this, it was equated that the CNC milled moulds would be tailored for minimization of milled height and the panels were situated in the stock material with this consideration. This included a minimum of 20cm of EPS height for stabilization and an offset of 5cm for boundary walls to sustain casting.

This comparison resulted in 14 stacks of for the case of the layered moulds, with variable heights and 135 individual elements for the case of CNC milled moulds. More relevantly, the first case represented an expenditure of approximately 42 m2 of material volume, while the CNC milling scenario resulted in approximately 89 m2. As such, the stacked moulds strategy could possibly correspond to a 50% reduction in material waste (Figure 4.71 b,c)).

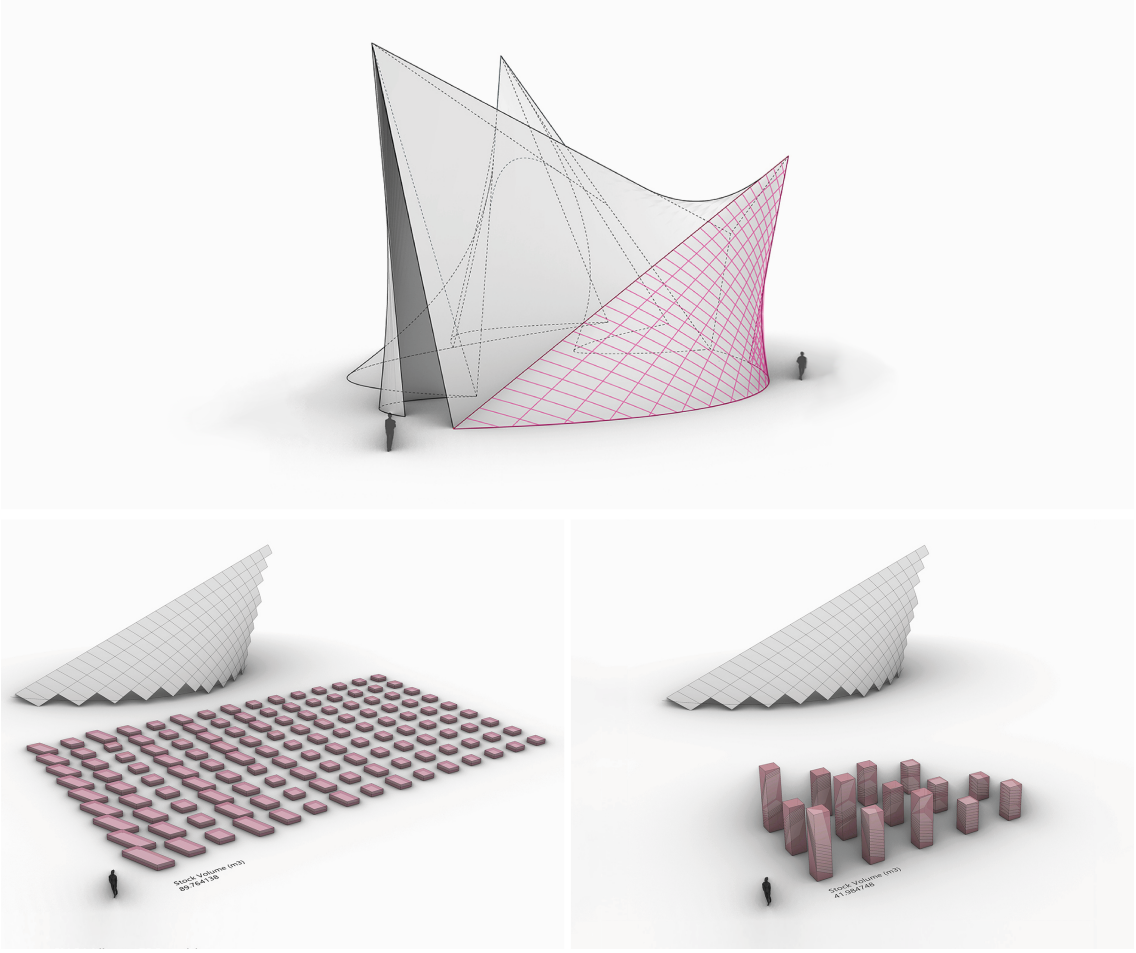


Figure 4.71: Comparison test between stacked molds and 3D milled molds for PHA: a) surface subdivision with one ruling direction and a perpendicular direction to achieve square stacks; b) resulting 3Dmilling moulds for all considered panels of PHA; resulting mould stacks for all considered panels of PHA

4.4.6 PH E section prototype

Following the previous experiments, in order to actually assess the possibility of rebuilding the complex concrete surfaces of the Philips Pavilion, an experimental prototype was devised for the production of a small section of another hyperbolic paraboloid surface of the pavilion, PH E (Figure 4.72a)).

For this final prototype, the previously developed square subdivision was used that divided the surface along a ruling direction and a non-ruling directions (Figure 4.72 b)), emphasizing the curved nature of the surface. To achieve this subdivision solution, again a projection plane (*a*) was found that was perpendicular to all planes containing the ruling direction (*rd).* The projected surface area was subdivided into squares with approximately 1m and this grid was projected back to the surface, generating 271 patches which contained two straight sides and two curved sides. From these, a section was extracted in the most curved area of the surface, composed of a set of 9 panels in a 3 x 3 matrix, corresponding to an overall area of 10.68 m2 (Figure 4.72, (Figure 4.73)).

In order to conform to existing EPS block dimensions and ease of handling, the panels were scaled down to the 1:2 scale, to an area of 5.34 m2 which resulted in projected square dimensions of 0.5cm x 0.5cm. The same grouping and surface translation algorithm was employed, with a surface separation of 5 cm between closest points, to create sturdy EPS sections. This resulted in a single 50 cm by 50 cm by 100 cm EPS parallelepipedic stack, containing all 9 panel surfaces (A1,A2, A3, B1, B2, B3, C1, C2, C3) (Figure 4.72 d)).

Simulation and toolpath generation was again done in the Grasshopper plugin for Rhinoceros, with the Kuka|prc software. The same configuration setup developed in previous experiments was used, concerning the definition of cutting paths from the panel surfaces and the adequate cutting speed.

The stock geometry was positioned upright in the cutting space and in this case, instead of creating separate cutting routines for each surface, a complete program was created that chained all nine cutting paths in the same routine, starting from the top section (A1), slicing surface by surface until the bottom one (C3). An exterior plane above the stock volume was also defined so that the cutting tool would always return to a safe position between each cut, with the added benefit of not needing to remove mould parts between the cutting procedures (Figure 4.74).

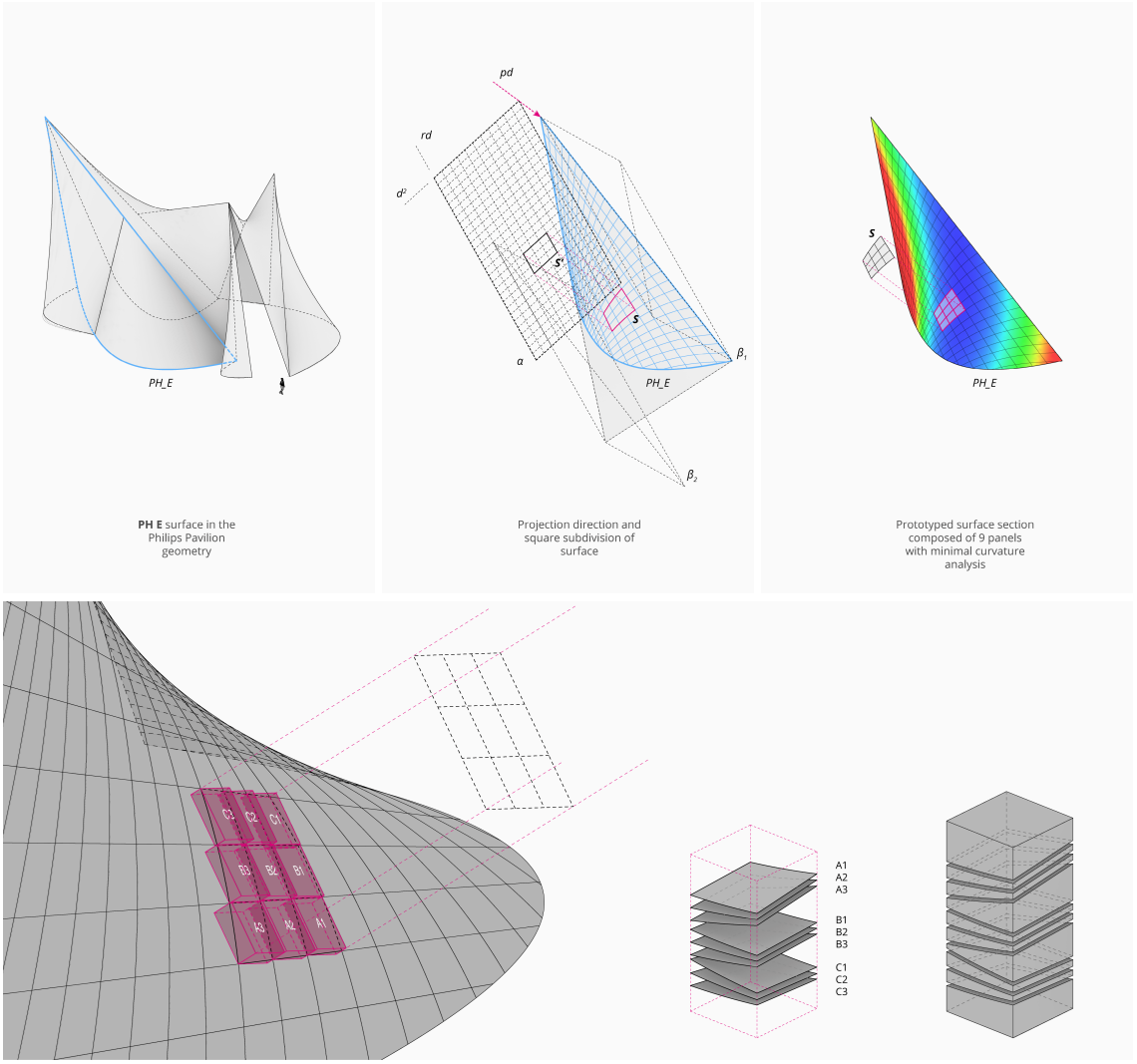


Figure 4.72: PH E surface subdivision and stack creation. a) Original surface; b) square surface subdivision in plane perpendicular to planes containing one ruling direction; c) resulting set of 9 panels and minimum curvature analisys of the area; d) boundary projection, surface patches reorientated in stack and simulation of final mould parts.

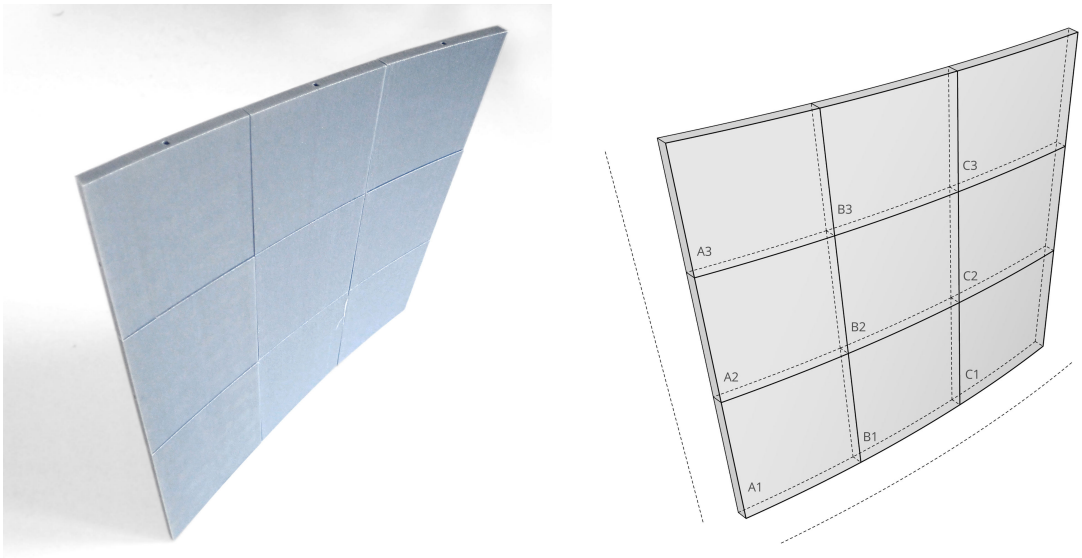


Figure 4.73: 3D printed test model and 3D model of the nine prototyped panels.

After an initial failed casting experiment[8], the mould design and corresponding program was improved with 2 added horizontal sections (S1 and S2), dividing the panels in groups of three, to increase EPS resistance to concrete casting pressures and prevent any buckling from occurring inside the moulds.

The final cutting sequence was completed in a process of 11 cuts, one per surface plus two for separation of each set of three surfaces (Figure 4.75). The entire process was concluded in approximately 15 minutes. The resulting stack was composed of 13 mould sections, which were then disassembled and reassembled into the original three by three matrix surface to verify the continuity between panels and overall accuracy of the moulds parts (Figure 4.76; Figure 4.77).

For the construction of the moulds, the layered stack was placed horizontally, inside a 2 cm thick plywood formwork shell, leaving one of the straight edges facing upwards. The mould sections were separated with the desired panel width (5cm) into groups of three and fixed to the plywood in all interior surfaces. The plywood shell was then closed and clamped, leaving the top side open for vertical casting in the nine voids left by the EPS sections (Figure 4.79). In preparation for the casting process, no postprocessing was done on the EPS surfaces and a simple coating of demoulding oil was used to ensure a correct casting and demoulding of the panels and to minimize the overall production time and costs.

Again, considering the closed mould design with the desired panel geometry and the difficul-

[8] The failed experiment was due to inadequate fastening of the individual mould sections and uneven casting of the voids. In this case, one of the mould sections was displaced laterally, deforming the adjacent panels.

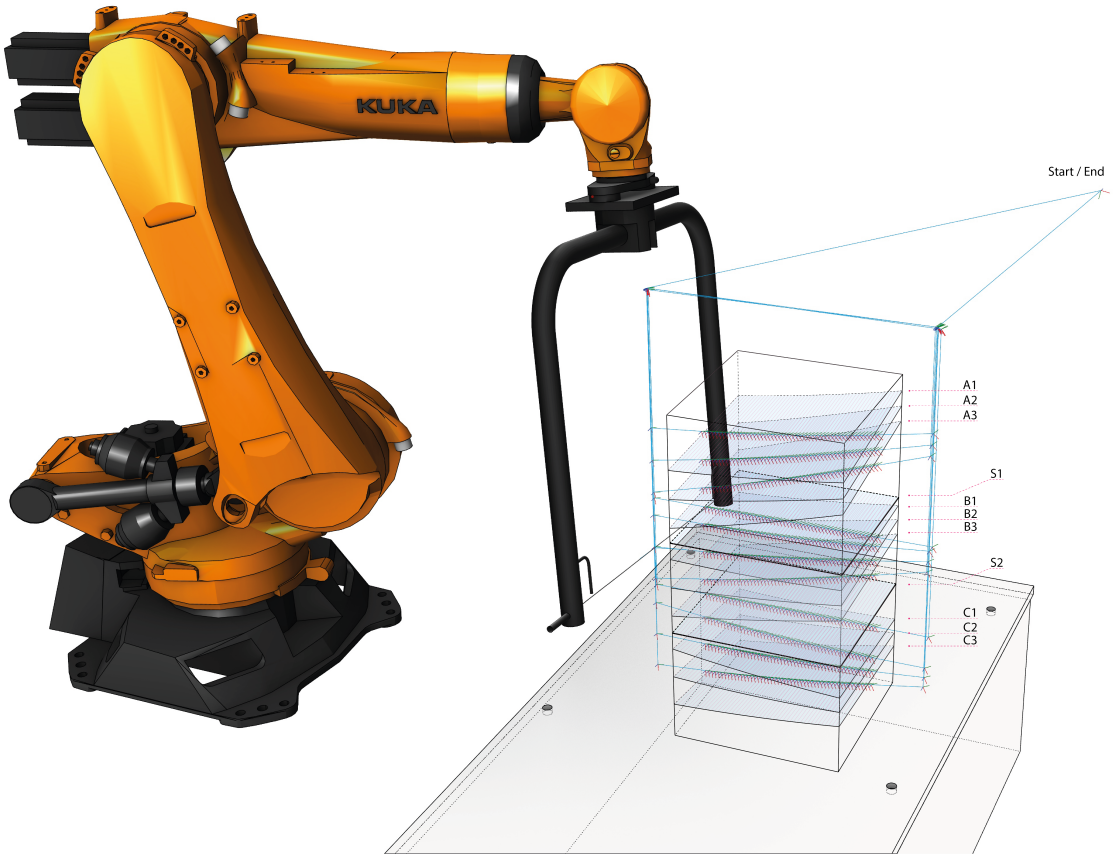


Figure 4.74: Toolpaths for complete cutting routine of final mould stack (9 panel surfaces and 2 separation surfaces).

ties of vibrating and applying regular reinforcement meshes, mix similar to the previous experiments was used, composed of self-compacting concrete, consisting of grey Portland cement, fine aggregates and fillers, combined with polyprolylene fibers for reinforcement. It was mixed in 2 batches as shown in Figure 4.78. Casting was executed sequentially, in groups of 3 panels, maintaining a constant pour hight, in order to further prevent differences in pressure inside the individual voids and minimize the lateral pressure of the concrete on the EPS moulds parts. The panels were demoulded after 8 days of curing time and assembly tests were conducted to verify the final geometry of the precast panels geometry.

After demolding and transportation, a substructure for the panels was built and they were manually assembled as ilustrated in Figure 4.80 and Figure 4.81



Figure 4.75: Cutting sequence for prototype stack (first iteration before adding S1 and S2). a) initial top position; b) approach to surface level; c) hot wire entry; d) patch cut; e) hot wire exit; f) rise to safe position, g) safe position; h) descent to next surface level; i) final stack (9 cuts).



Figure 4.76: Front view of final stock volume after 11 sections (second iteration).



Figure 4.77: Final stock volume and assembled mould segments to confirm surface geometry.

Batch 1 mix (48 litres)	Quantities (kg)
Cement (CEM I 42,5)- R) - Maceira	30.280
Limestone filler	13.626
Fine sand	29.901
Medium Sand	29.901
Water 1	2.385
Water 2	7.154
Super plasticizer (Viscocrete 3005)	0.578
Fibres - Meyco Fib SP 630 (BASF)	0.288

Batch 2 mix (64 litres)	Quantities (kg)
Cement (CEM I 42,5)- R) - Maceira	40.373
Limestone filler	18.168
Fine sand	39.869
Medium Sand	39.869
Water 1	3.179
Water 2	9.538
Super plasticizer (Viscocrete 3005)	0.771
Fibres - Meyco Fib SP 630 (BASF)	0.384

Figure 4.78: Mixes for the two batches of concrete necessary for the nine panels.

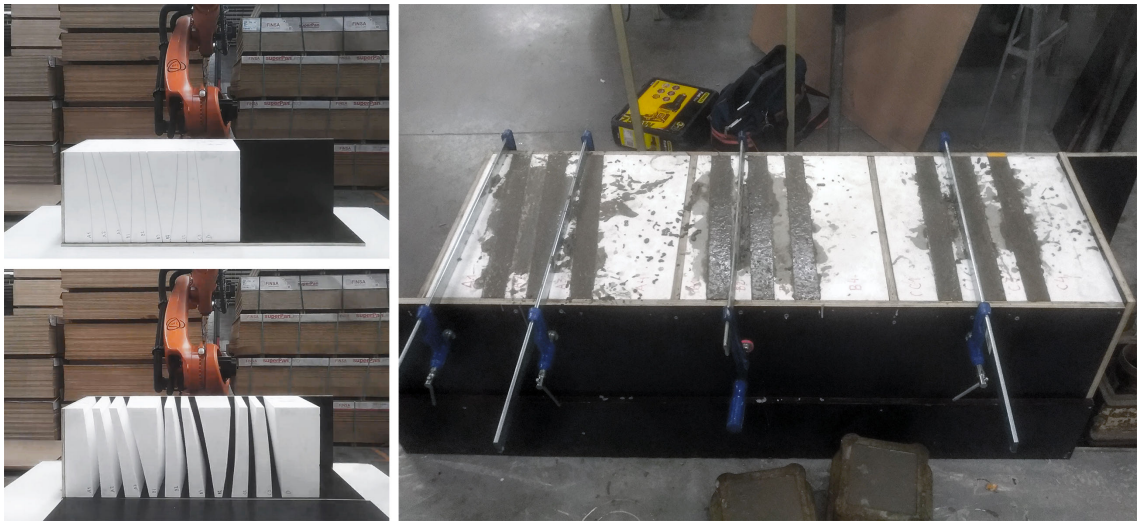


Figure 4.79: Assembly of mould sections in the plywood shell (first prototype without two extra sections) and final formwork after casting of the voids (final prototype).

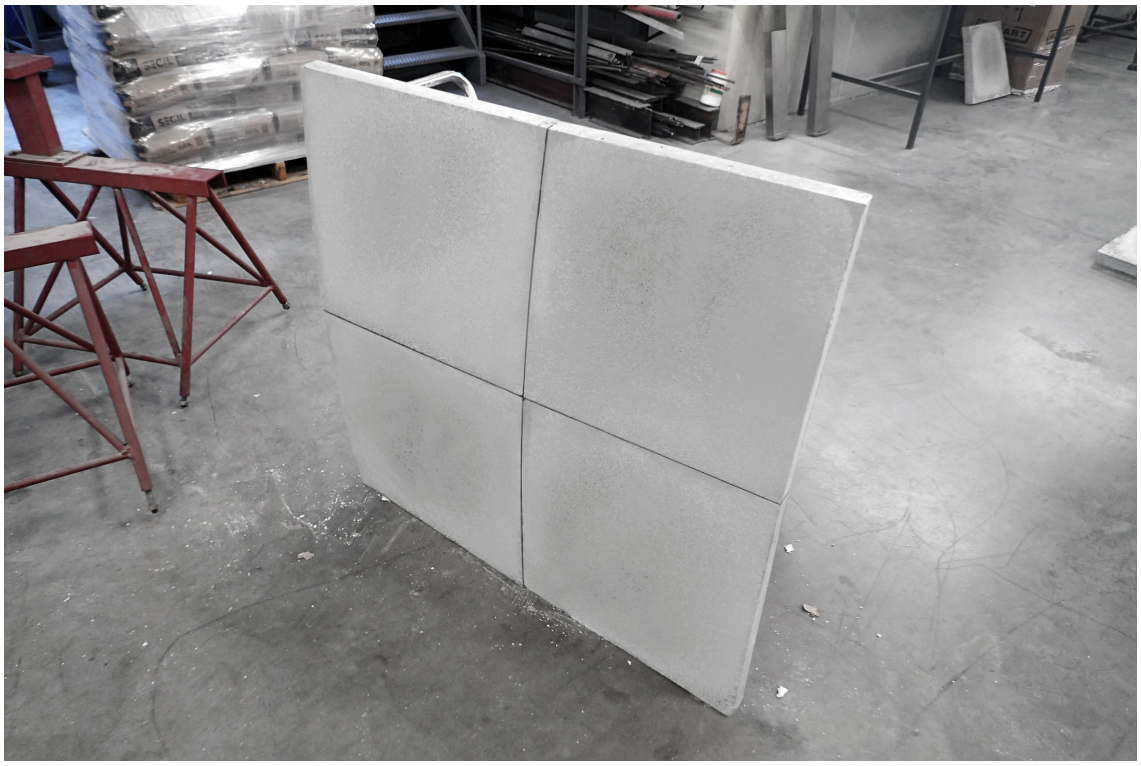


Figure 4.80: Assembly of four of the nine panels after demoulding.

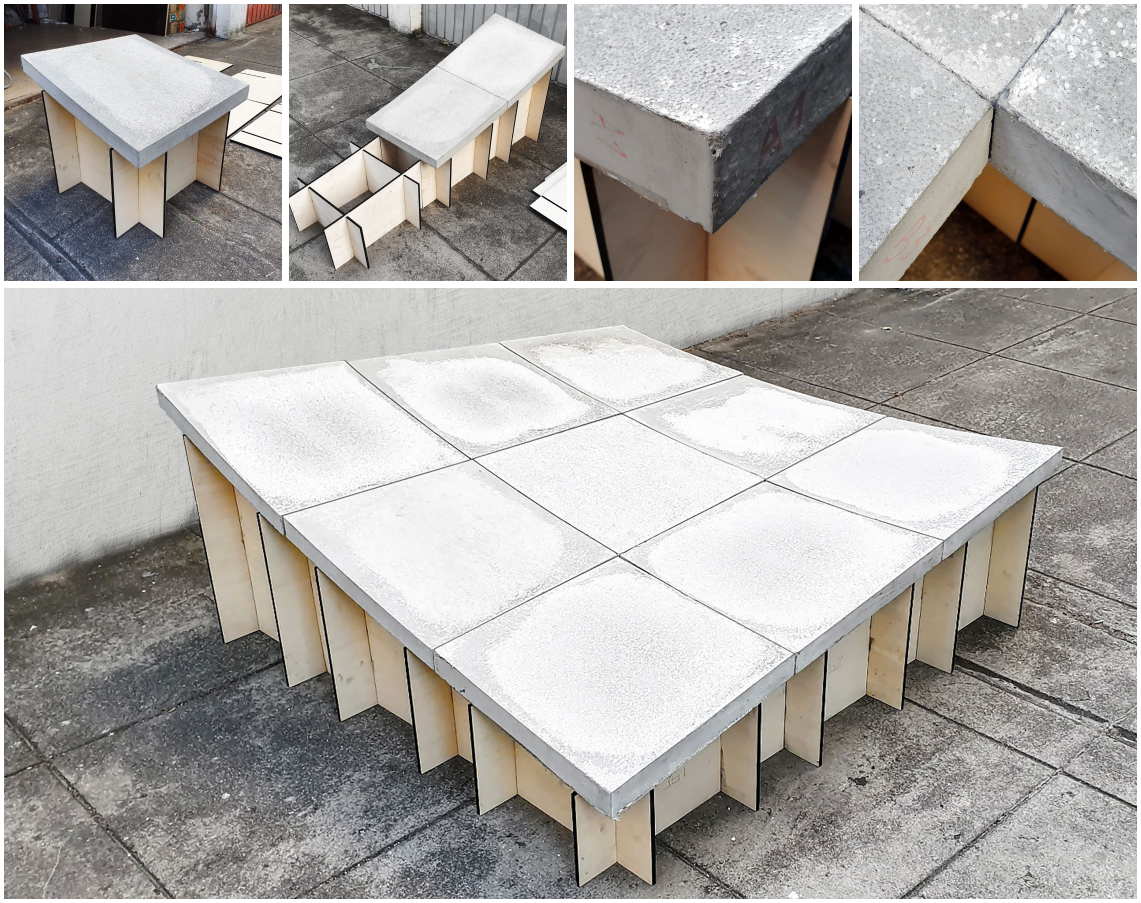


Figure 4.81: Final assembly: a) single panel; b) second panel; c) detail of panel edges; d) detail of joint of 3 panels; e) final assembled surface.

4.4.7 Results

In the development of the described research, different constraints and characteristics of the proposed process became apparent that are discussed here, before conclusions are drawn. Regarding the geometric constraints of the stacked strategy and required design, some consideration should be taken in selecting the projection direction of the subdivision in order to avoid excessively vertical panels inside the stock material and optimize material usage. Also, the process assumes (as the original construction method), that the panel sides are not perpendicular to the surface curvature. This evidently prevents its usage in stereotomic assemblies, where such characteristic is fundamental, without using variable section stacks[9] and more cuts. These inherent constrains clearly position this strategy between the complete dependency on ruled boundaries of the original casting solution and the complete geometrical freedom of the CNC milling process. Moreover, although the non-square EPS blocks necessary for some of the studied surface subdivision cases would complicate formwork design, the advantage of building the entirety of the ruled surface, using only 2 types of mould stacks, present in some of the tested subdivision designs, could still represent considerable benefits in terms of construction optimization.

Regarding the Robotic Hotwire Cutting, as discussed before, the process presented considerably reduced times when compared to normal CNC machining for the same surface area. Considering approximately 120min/m2 to 240min/m2 for CNC milling (depending on desired surface smoothness) and the extrapolation of 240s/m2 for RHWC, this represents a 30 to 60 fold decrease in fabrication time for RHWC. These times were somewhat offset by the added time and manual labor of assembling of the mould stacks into the plywood formworks. However, these tasks can be similar for EPS moulds independently of fabrication strategy. Nevertheless, the increased output of the process in an industrial setting would also mitigate this aspect.

As expected from previous experiments, the surface quality of the concrete panels was not comparable with precast panels using other strategies, such as regular wood formwork or moulding tables using membranes, due to the EPS porosity. Nevertheless, improvement measures can be taken to achieve the same qualities, through the use of EPS coatings, or an interface layer between EPS and casting, without compromising the overall process. Moreover, the use of the closed moulds with lateral panel sides facing the plywood panels, resulted in smoother and much more precise boundaries in the finished panels when compared with the previous MSE panels experiment which presented bevelling along edges perpendicular to the perimeter shape.

At the technical level, other advantages can also be found, namely: 1) the reduction of process-

[9] For instance, a slightly pyramidal stack with the surface patches correctly ordered inside.

ing times, 2) a possible reduction in transportation and storage costs (through volume optimization of the parallelepipedic shapes), 3) ease of integration with existing precast practices, without the need for other complex digital fabrication procedures. All such advantages represent important chances for an increased availability of digital fabrication strategies in current construction practice.

Past experiments in rebuilding the Philips Pavilion were mostly focused on the construction of continuous or (mostly continuous) hypar surfaces in concrete. While this was certainly a possibility considered by the original architects, we believe that the final built pavilion expressed a more nuanced story of technological innovation in precast concrete construction, which fuelled the particular architectural expression and tectonic relevance of the Philips Pavilion. At this architectural level, this research demonstrates a possibility of rebuilding the Philips Pavilion within this spirit, maintaining the original tectonic character of its ruled, prefabricated surfaces in a reinterpreted design, specifically for RHWC. On a broader scale, this research shows how digital fabrication technologies can be configured for enhanced sustainability and efficiency, while also driving architectural language in coherent tectonic expressions, maintaining strong relations between construction and design.

The results of the experimental prototype were evaluated and extrapolated to simulate a full reconstruction of the Philips Pavilion in order analyze the consequences of the developed process and compare it to other existing processes. We believe that the RHWC process in conjunction with the stacked mould system presents clear advantages to traditional mould systems and several other digital fabrication strategies. It leverages the speed and efficiency of Robotic Hot Wire Cutting, with subdivisions strategies to maximize production efficiency and thus attain an increased sustainability by decreasing volume waste by roughly 80% when compared with current milling strategies. At this technical level, other advantages can also be found, namely the reduction of processing times (and output volumes), transportation and storage costs by volume optimization and the ease of integration with existing precast practices.

At an architectural level, this research demonstrates the possibility of rebuilding the Philips Pavilion, while maintaining the original tectonic character of its ruled, prefabricated surfaces. Furthermore it intends to go beyond this case study, by demonstrating how digital fabrication technologies can be configured for enhanced sustainability and efficiency, while also driving new architectural languages in coherent tectonic expressions, from design to materiality.

This established a different possible vocabulary for rethinking the design of the Philips Pavilion surfaces without the need to conform to the ruling directions, but in line with the existing ar-

chitectural logic of prefabrication with an expanded design space, directly linked to this digital fabrication technology.

4.5 The Corkcrete Arch: A lightweigth tectonic prototype

4.5.1 Objectives

The experiments developed in the previous sections of this thesis focused on understanding the technical capabilities of RHWC, design limits and potentials as well as its relevance for the fabrication of moulds for casting non-standard architectural concrete components. With these previous experiments, general processes for the use of RHWC in this context were sufficiently validated. Nevertheless, the prototypes developed thus far used as a design problem, the materialisation of curved ruled surfaces, through the use of prefabricated panels, but doing so without designing complete structures. In The MSE Panels (section 4.3) and in Revisiting the Philips Pavilion (section 4.4), these issues were materialised in partial, scaled-down designs, with non self-supporting test prototypes, in a laboratory environment.

Thus, the CorkCrete Arch was developed as a more complete design-based research activity focused on using robotic fabrication technologies in the production of a novel design and building system. By exploring the combination of two different materials – cork (in the form of ICB – Insulation Cork Board) and Glass-fiber Reinforced Concrete (GRC) - the goal was to merge the sustainable and insulation properties of the first with the structural efficiency and finishing of the second. The result was a modular, lightweight and performative material system, suited for customized prefabrication and easy on-site installation.

Relating to the general scope of this thesis, the main objectives for the Corkcrete Arch prototype were:

- Design a 1:1, self-supporting tectonic structure for robotic fabrication, with a particular focus in RHWC.
- Develop a new dual material lightweight construction system usable in customised designs
- Implement and validate the complete design to production workflow of the prototype, from digital model to physical construction, in an prefabrication industrial setting.

The proposed building system was tested through the design and construction of an arch structure. Featuring double-curved and textured cork panels combined with ruled-surface GRC elements, its geometry challenged the use of robotic fabrication technologies for its production. Since it was not a single material installation, like in the previous prototypes in this dissertation and many current robotic experiments, the process had to coordinate the different physical tolerances resulting from employing different materials and different fabrication processes, taking place in different locations (i.e. laboratory, factory and on-site).

Working in collaboration with industrial partners, from the cork and GRC fields, this experience envisioned and tested a fabrication strategy with both materials that revealed to be very productive and efficient for both areas. While the Corkcrete Arch was the subject of different design and fabrication strategies (due to its material duality), considering the theme of this thesis, this chapter will focus more specifically on providing a detailed description and analysis of the robotic fabrication process used in the production of the GRC components.

The next sections follow the design to production workflow, for this final experimental work (Figure 4.82). The Corkcrete Arch was a multidisciplinary effort, developed by the complete team at the DFL lab and partners. This thesis' author focused on the GRC fabrication process, which is also the main focus of the following sections.

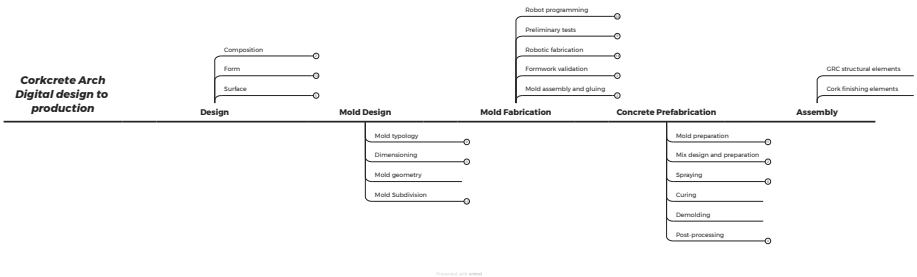


Figure 4.82: General view of the Corkcrete Arch GRC design to production workflow.

4.5.2 Design

As the name implies, the Corkcrete Arch was conceived as a self supporting arch structure, 280cm wide and 260cm high. The overall form of the CorkCrete arch was driven by two main factors: a central catenary curve and the specificities of robotic fabrication technologies. On one hand, the catenary curve was used to provide structural integrity to the arch. On the other, robotic fabrication technologies were used as a design driver to define respective geometries of

the different material surfaces. The result was funicular catenary arch structure with a composite interior/exterior materiality.

The material character of the arch was thus an important design consideration. After early material prototype tests were conducted, mixing cork and white concrete in different combinations (Figure 4.83), cork was selected for the outer surface of the arch and white GRC for the inner one. This was done to better highlight the differences in the materials and to have structural GRC elements in the inner surface and insulating cork in the outer part of the arch.

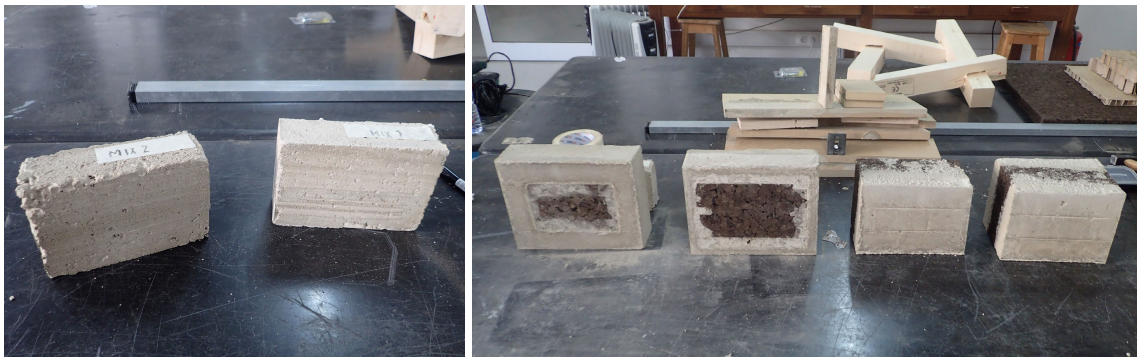


Figure 4.83: Early material studies. a) cork and concrete mix with different ratios; b) different combinations of concrete and cork envisioning composite panels.

In terms of geometry, the main catenary curve and two offsets were the sole geometric entities from which the surfaces of the arch were parametrically generated. Thus, from this curve, two main surfaces were created. The diagrams on Figure 4.84 show the creation of the main inner (GRC) and outer (cork) surfaces of the arch. The outer surface is a general double curved surface, generated through lofting three curved sections along the center catenary curve. It was designed to take advantage of the greater geometric freedom of CNC milling, envisioned as the transformation process of the cork material.

The inner surface of the arch was designed as an exploration of intersecting ruled geometries for fabrication with robotic hot-wire cutting. These were generated by sweeping two straight lines at either base of the arch, with a "V" shaped section at the apex of the arch, creating a set of ruled surfaces that start flat at the base and develop into a marked central "seam" at the top of the arch.

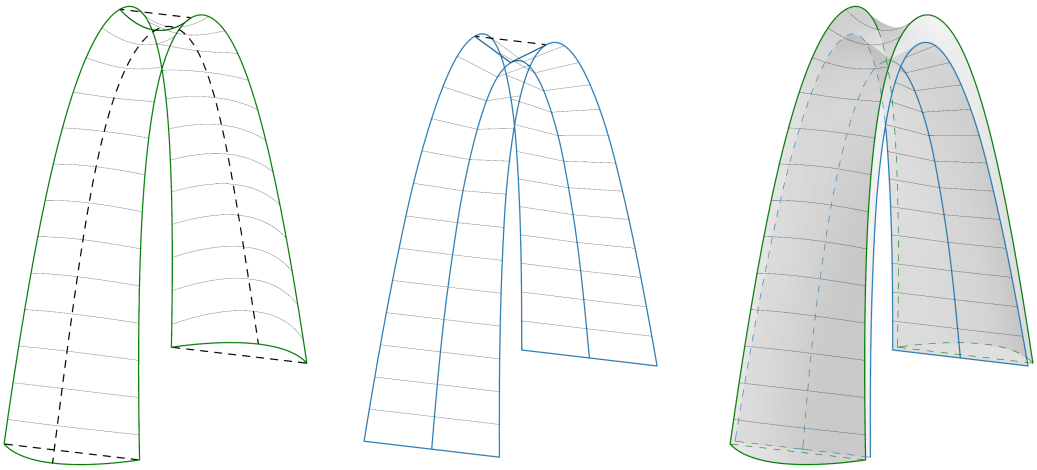


Figure 4.84: Inner and outer surfaces of the Corkcrete Arch. a) outer double curved surface for CNC milling of cork; b) inner ruled surfaces for GRC and RHWC; c) surfaces in position (image by Pedro Varela).



Figure 4.85: Corkcrete arch render. Note the faceted line separating the cork and GRC materials and the variable thickness of the GRC elements (image by Pedro Varela).

Designed specifically for prefabrication, the arch was also created as a modular composite system, thus both the cork and GRC surfaces were subdivided into separate panels. The separation between the cork and GRC surfaces was created through a central polyline, composed of straight segments, resulting in planar surfaces for the underside of the cork panels and upper side of the GRC panels. This was done to create an interesting contrast to the arch's overall inner and outer curved surfaces. It also had the benefit of ensuring that (further down the line) the envisioned cork panels would not need to be milled in their underside. Figure 4.85.

Employing the inherent characteristics of Glass Fiber Reinforced Concrete (GRC), these structural components of the CorkCrete arch were formulated as slender panels with 15mm in thickness and lateral folds with a variable height. This height increased from the thinner base towards the thicker apex of the arch, starting with a minimum of 40mm, reaching a maximum of 100mm.

The final design of the arch is thus built from the assembly of 3 structural GRC elements and 18 cork panels (Figure 4.86). This subdivision was created using the straight segments of the central separation line, with its vertices aligned with the separation lines of the GRC and cork elements. Thus, structurally, the arch is composed of three main GRC panels, named A,B and C for convenience. Parts A and C correspond to the lateral legs of the arch and each has 4 corresponding cork panels. Part B corresponds to the top section of the arch, having 10 cork panels. The interface surfaces between the GRC components are locally perpendicular to the original catenary curve to maintain the funicular behaviour of the arch.

Finally, the apparent interior and exterior surfaces of the corkcrete arch were envisioned as expressions of each fabrication technology used. The cork panels were designed for expressive texturing from subtractive milling processes with custom-made tools. The interior surfaces were designed as contrasting smooth GRC surfaces.

4.5.3 Layered mould for GRC

Focusing on the production of the 3 GRC panels, in order to address the fabrication difficulties put forward by the complex geometry of the Corkcrete Arch, the materialisation of these elements explored a revised mould solution, solidifying the knowledge developed in the previous prototypes, regarding robotic hot-wire cutting of formwork and adapted to produce the desired GRC panels and to be combined with the cork elements. Figure 4.87 illustrates the adapted layered mould logic to the specific case of the Corkcrete Arch.

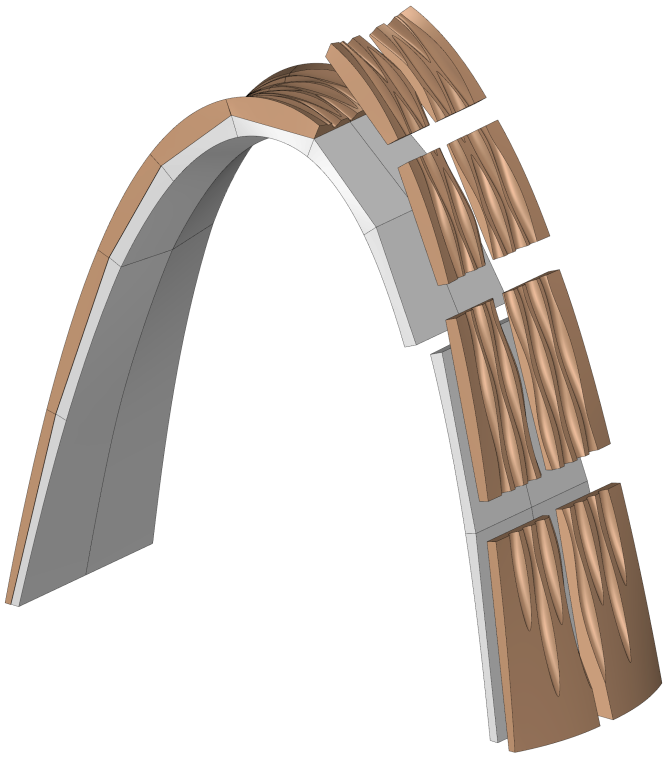


Figure 4.86: Corkcrete arch visualization 3D model with exploded GRC and cork panels (image by Pedro Varela).

In several aspects, the mould typology used was similar to previous explorations. It still featured the subdivision of a mould geometry into several layers cut from a single EPS block and assembled into a final layered mould. Nevertheless, other features dictated differences in the case of this prototype. Compounding on the general variable radius curvature of the arch, the specific geometry of the 3 GRC panels posed several challenges:

- **Inner surfaces**: the central "seam" design feature means that for each panel, its interior face is not possible to be generated in one single wire pass, being the intersection of two ruled surfaces.

- **Side surfaces**: the lateral faces of the GRC panels perform as structural reinforcement of the thin panels, and were also designed as a continuous ruled surface, slightly curving inward and increasing in height from the base to the apex of the arch. This meant that the lateral sides of the GRC panels are not perpendicular to the surface as is usual in common GRC panels but are in themselves ruled surfaces that develop along the perimeter of each panel.

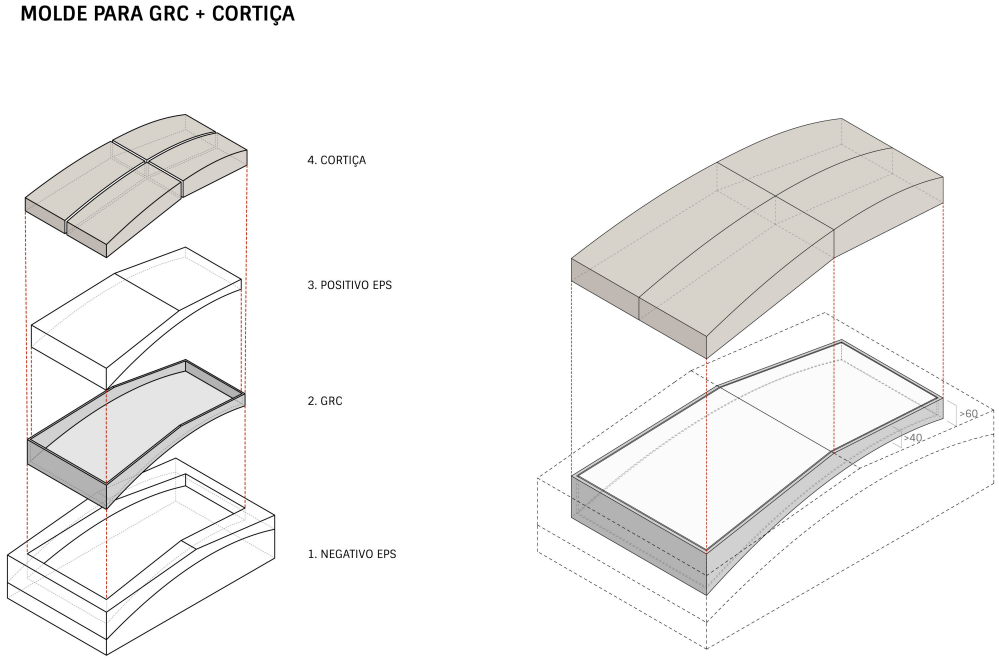


Figure 4.87: General concept of GRC + mould + cork panels.

- **Part size**: Each part is significantly larger than our previous experiments with RHWC, requiring special arrangements of stock material volumes.

The geometric complexity of these design elements was heightened by the necessity of fabricating a corresponding negative mould which had to be open for GRC spraying. The main fabrication challenge was thus the production of a large-size[10] concave ruled surface mould with variable, ruled lateral walls. This kind of geometry requires a customized mould that can not be achieved with a single sweep RHWC process such as the ones experimented with in the previous prototype. Thus, the moulds for the Corkcrete arch were designed form the bottom up with consideration to the geometry of the GRC panels and the fabrication technologies available.

Following the concept of slicing in the layered mould strategy, the moulds for the Corkcrete Arch GRC panels were designed by identifying 3 surfaces to be sequentially cut: the **interior GRC surface**; the **perimeter layer** which would define the shape of the GRC side walls and the overall boundary geometry of the panels; the **exterior surface** that would define hight limit of the GRC side walls and the flat top planes of the GRC components Figure 4.88.

[10] The available stock EPS volumes were approximately 100x50x50cm.

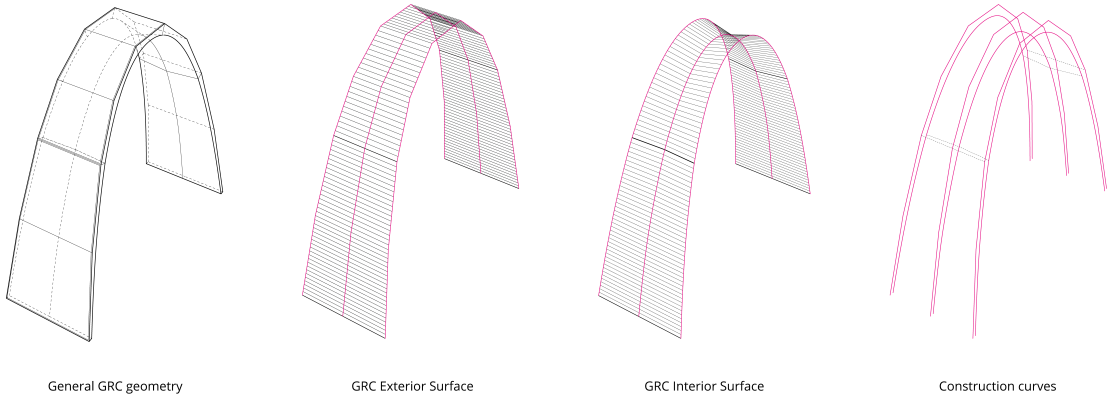


Figure 4.88: Corkcrete arch GRC panel geometry: a) full assembly; b) exterior planar surface; c) interior ruled surfaces; d) extracted main input curves for fabrication.

Working within this general strategy and identifying the previous mentioned difficulties, a mould solution was devised that started by addressing the issue of creating the large concave interior surface. This was done by dividing each GRC panel mould in two parts (A1, A2; B1, B2; C1,C2), along its center longitudinal seam, resulting in 6 moulds halves for the 3 GRC panels. These could therefore be cut separately and then glued together. This guaranteed the possibility of accurately creating the ruled concave surface with RHWC.

Creating the ruled perimeter of the GRC panels was addressed with a similar strategy to the MSE panels prototype - the creation of a central part, responsible for defining the perimeter shape of the panels. Improving on the work developed there, this section was envisioned for fabrication through CNC flank milling.[11] This allowed to quickly create deep perimeter cuts with the radius and height of a large milling bit. Because the CNC milling setup used allowed for 6-axis of freedom and the movement of the mill bit can be considered a line in space, this milling operation naturally results in the description of the necessary lateral ruled surfaces. This solution greatly improved the time and accuracy of this stage due to the inadequacy of RHWC for cutting such small surface areas.

The description of the exterior planar surfaces did not envision any difficulties for their materialisation through RHWC. As in the case of the MSE panels, the definition of a perimeter part, in combination with the exterior surface layer resulted in an excess center core part. While in the previous experiment it was discarded, in this one, it became a part of the complete moulds, serving as a filling material to define continuous flat exterior surfaces for the cork panels.

[11] Flank milling is a process through which the milling bit is used in all its heigh for cutting, aligning the tool side with the surface desired for cutting. Opposite to regular point milling where only the tool tip is used to cut.

As shown in Figure 4.89, the final mould design for each GRC panel was composed of 4 main parts (8 symmetrical parts glued together):

- **Base part** - defining the interior surface of the arch and main area where GRC was to be sprayed.
- **Perimeter part** - defining the overall shape of the panel and the hight of the lateral GRC sides.
- **A stay-in-place core** - as filling material for the thin GRC panel cavity.
- **Top part** - usable for closing the moulds and ease of transportation

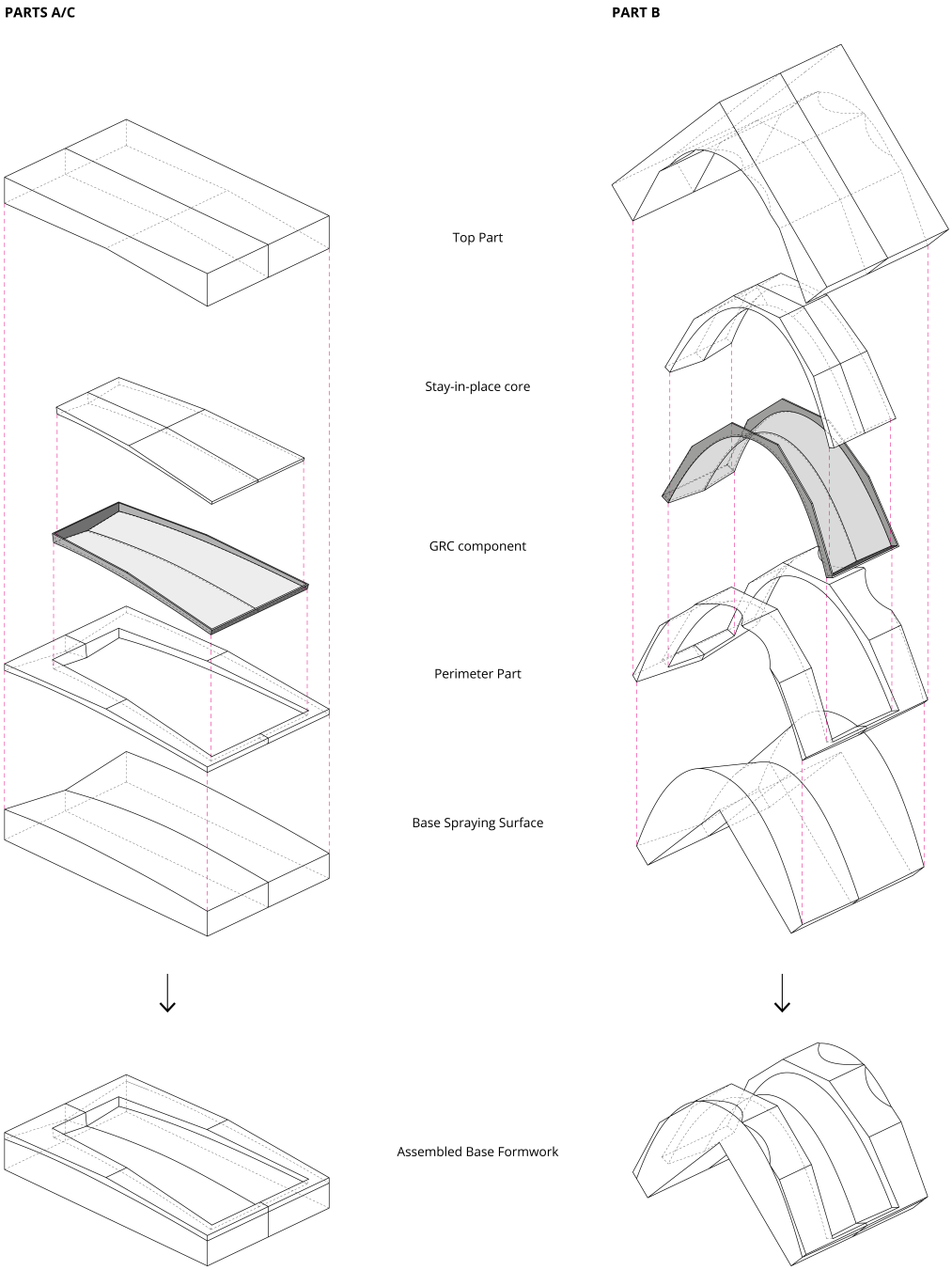


Figure 4.89: Constituent parts for the Corkcrete Arch moulds, with a simulation of the GRC element inside: a) arch elements A and C; b) arch element C.

4.5.4 Robotic fabrication

The fabrication of the moulds for the Corkcrete Arch entailed two main tasks: the actual robotic fabrication and the necessary assembly required from the specific mould design described previously.

While the mould design established the surfaces necessary to be cut, for the robotic fabrication, a particular ordering of these cuts had to be devised. This ensured that the geometry of the mould could be successfully materialized. The main issue in this ordering of cutting operations was avoiding having to reposition the original stock materials at any point in the cutting sequence. This would require recalibration operations that would add more time and possibly reduce the overall precision between the mould parts.

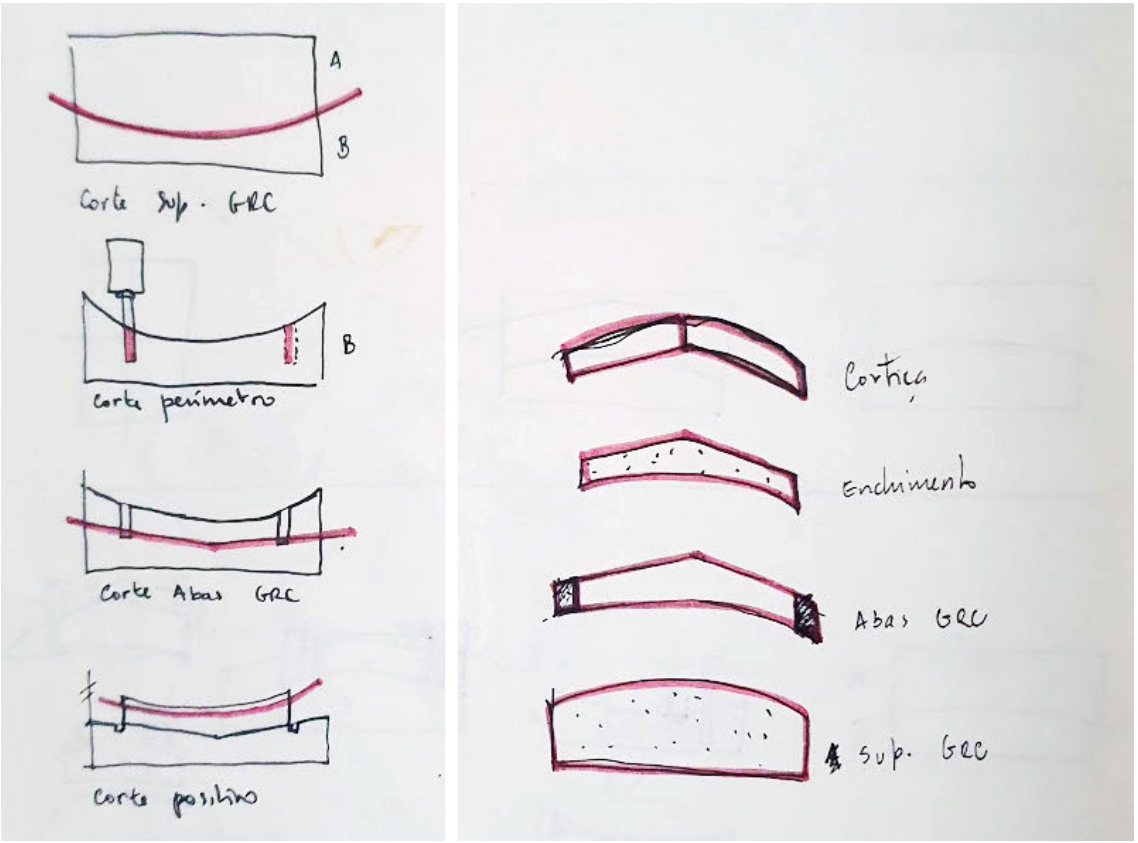


Figure 4.90: Sketch defining the general cutting sequence for the Corkcrete moulds (left). The mould is fabricated upside-down and repositioned for GRC spraying (right)

With these aspects in mind, the fabrication routines were composed of five cutting operations performed sequentially in the following order (Figure 4.90;Figure 4.91):

1. **Cut 1 - Axis Surface**: hot-wire cut of a planar section of the stock, defining the axis surface where both mould parts would later be glued. This cut was of great importance to provide a precise gluing plane as the factory finishing of the original stock blocks could not be used. After this cut, the stock material should be rotated and repositioned in the cutting table;

2. **Cut 2 - Interior Surface**: hot-wire cut to define the interior surface of the arch. After this cut, the resulting top half is to be removed;

3. **Cut 3 - Perimeter Surface**: milling of the ruled contour of the panel with a 20mm diameter bit, in a single pass.

4. **Cut 4 - Exterior Surface**: hot-wire cut, defining the planar surfaces for the exterior face of the GRC elements and separating the core and perimeter parts. Afterwards, the perimeter part should be removed, maintaining the core part in place.

5. **Cut 5 - Core surface**: hot-wire cut of the EPS core resulting from the previous operations to fit the interior of the panels. This cut was an offset of the original interior surface, to account for the thickness expected for the actual GRC panel, so that the core would not bulge out of the GRC sides.

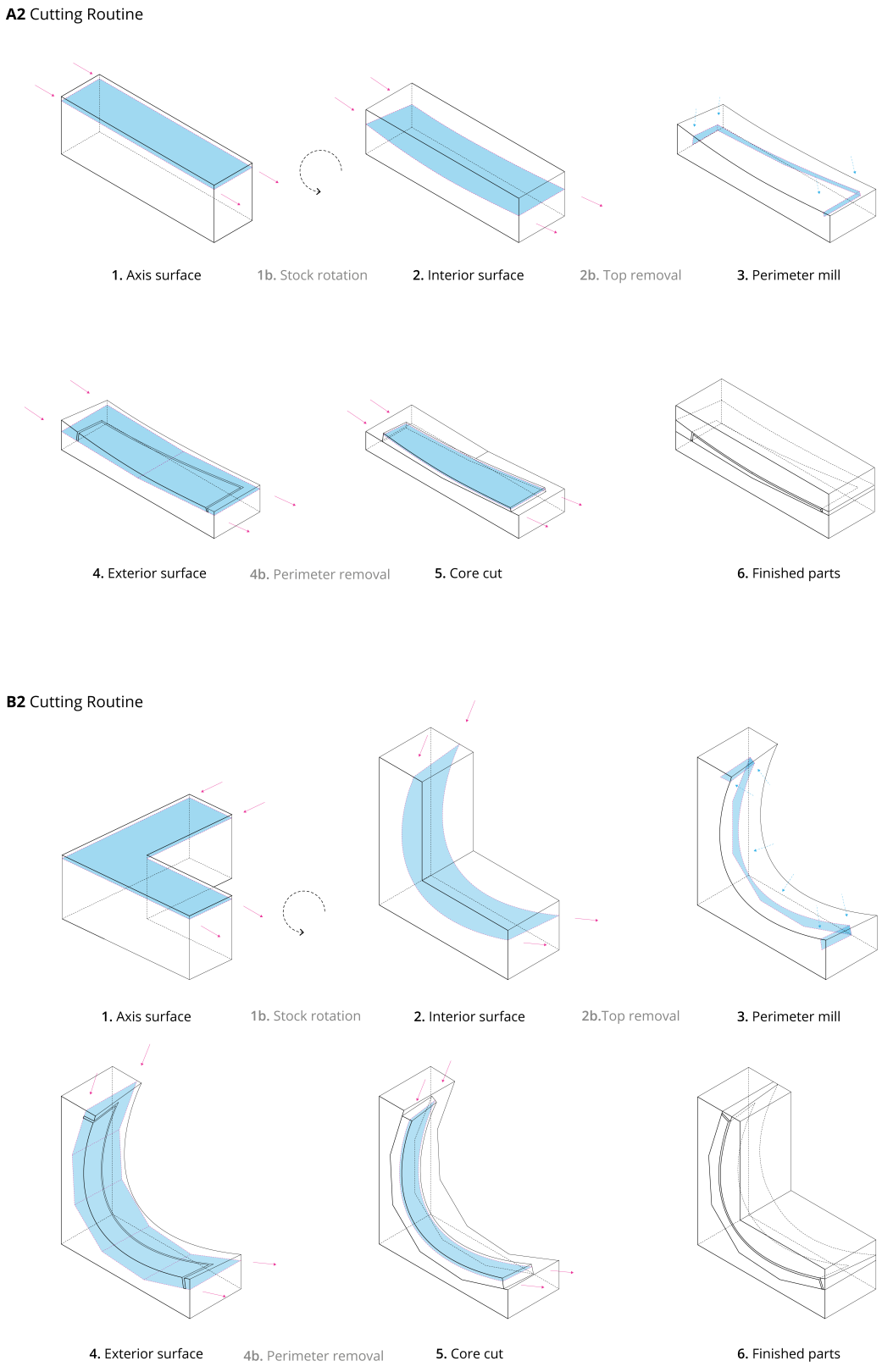


Figure 4.91: Diagram of all material surfaces expected from the full cutting routines for mould parts A2 and B2.

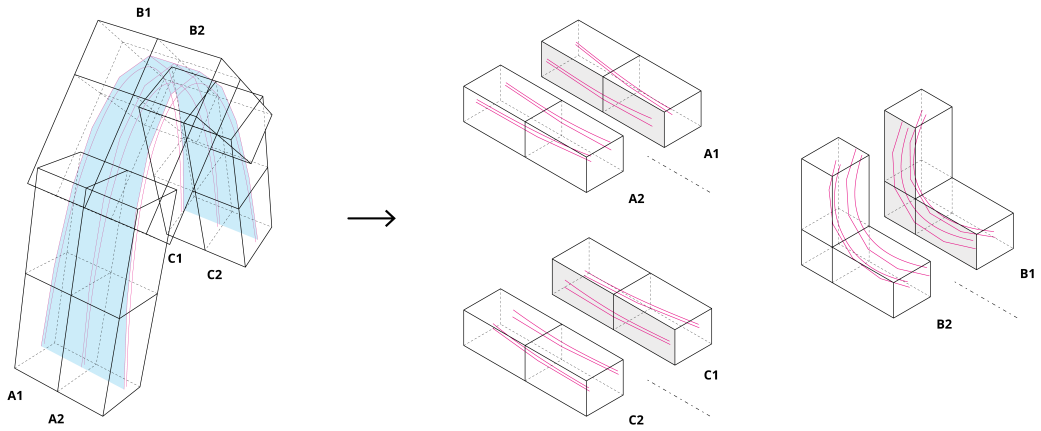


Figure 4.92: Relation between stock volume and the GRC panel geometry for the Corkcrete Arch. (Left) Stock volumes in the original arch position. (Right) Stock volumes and RHWC input lines oriented for fabrication.

To materialize the final 3 moulds, 6 stock volumes were created following the defined routines. For parts A and C, stock volumes with dimensions of 200x60x50cm were created by gluing 100cm long blocks. The moulds for the apex section (part B) required the assembly of an "L" shaped stock volume, using the same base stock material (Figure 4.92).

The relative position of the panel geometry inside the stock volumes was determined by several factors. As usual, reach of the end-effector was a relevant issue, but in this case, this positioning was also conditioned by the particular geometric features of the mould. Each mould half would have to have its central "seam" face coincident with a surface of the stock volume so that it could be glued with the adjoining one. Also, the panel geometry would have to be positioned as such that the gluing seams in each stock volume were aligned with the vertices of the edges of the exterior planar surfaces of the GRC panels and centered with the interior curved surface. One edge for parts A and C and 2 edges for part B (Figure 4.92). This was done envisioning that these gluing joints in the stock material would be later translated into the surfaces of the finished GRC components as other formwork traces in the studied examples of subsection 2.3.2 - Surface.

In the definition of the toolpaths for robotic fabrication, the only inputs used were two sets of lines for each cutting surface. These lines were the same as in the initial parametric definition that generated the design of the arch. For the interior and exterior surfaces of the GRC panel (cuts 2 and 4), they correspond to the longitudinal edges of those surfaces (Figure 4.92 b)).

Using the same methods already described in previous tests, tool path generation was conducted

in the Kuka|PRC Grasshopper plugin. For these surfaces this was done by using the pairs of input curves as directrixes of the desired surfaces and creating generatrices (rulings) from which the direction of the wire was extracted. A cartesian frame for each wire position was created along this direction with the addition of a singular exterior guide point for orienting the end-effector in the z direction.

Some extra considerations also were taken in the definition of these hot wire tool paths. While in most previous prototypes, the design surface (DS) was centred in the stock volume, in this case, due to the central seam, the design surfaces were offset to one side. Thus, while previously the center of the wire was positioned in the center of the desired design surface, in this case, it was centred with the stock volume,[12] maximizing the available cutting length. These features are visible in Figure 4.93, where the original ruling lines of the panels design surface are visible as well as the position of each cartesian frame.

The perimeter flank milling operation was generated using both exterior and interior edge curves, creating a "C-shape" path in both interior and exterior curves. These paths were offset 10mm from the original surface edges to account for the tool diameter (20mm) and were then used to define the milling bit orientation in a sweeping motion along these two edges (Figure 4.94 b)).

The core cut (cut 5) did not take any extra inputs and was simply an offset of all cartesian planes of the first cutting surface, along their z axis, defining a surface parallel to it. The parametric tool path generation algorithm created didn't require special considerations between parts A, B and C, depending only on the input lines given.

After the tool paths for each of the 6 mould parts were created, several tests and simulations for collision and reach checking were conducted, ensuring that all robot movements were feasible. These were performed using both simulated runs and analysis within in the Kuka|PRC environment (Figure 4.95) and by performing dry runs without stock material present.

Considering that some stock repositioning from cut 1 to 2 and a tool change would occur between cuts 2 and 3, the cutting routines were exported and run as individual programs (1 per cut) to better control each step. The final robotic fabrication process was developed following the established order and minimal adjustments or issues arose during this stage. Careful monitoring of the cutting speed and temperature was taken throughout the RHWC procedures[13]. Also,

[12] To achieve this, each center point was moved along its ruling line to become centred in the stock width, thus maintaining the resulting ruled surface.

[13] In the interior surface for the A1 part, the hot wire was inadvertedly and momentarily stopped, creating a visible kerf line in the mould that became visible in the final GRC surface.

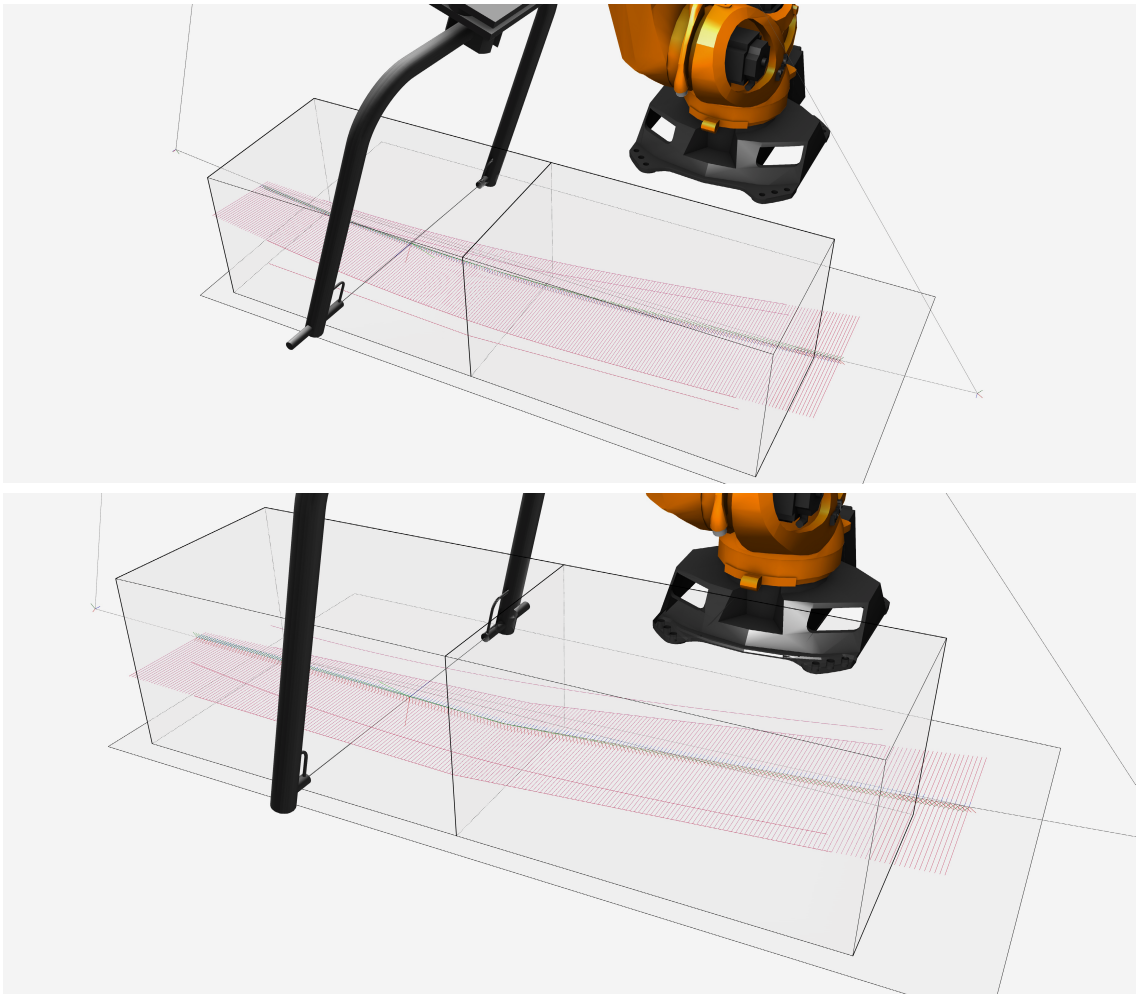


Figure 4.93: Input curves, ruling lines along the design surface for panel half A1 and hot wire cartesian planes. a) interior surface; b) exterior surface.

some EPS deformations during rhwc processes[14] were addressed with the addition of weights.

Excluding initial calibration times and tool changing for cut 3, the fabrication routine for each mould half was completed in approximately 10 minutes for all 5 cuts. The following photos in Figure 4.96 and Figure 4.97 illustrate the main cuts for the final robotic fabrication of the moulds and the resuting parts before assembly.

As layered moulds, after the fabrication process assembly and gluing were necessary creating the final mould configurations. Interior surface parts of each mould half (eg. A1 and A2) were aligned and glued along their axis surface. The perimeter parts were then placed and also glued to the interior surfaces (Figure 4.98). Because the GRC spraying process requires an open

[14] These tend to occur for cuts where the resulting EPS layer is very thin and lifts up or sags down (cuts 1 and 5), potentially resulting in geometric deformations in the cutting surface.

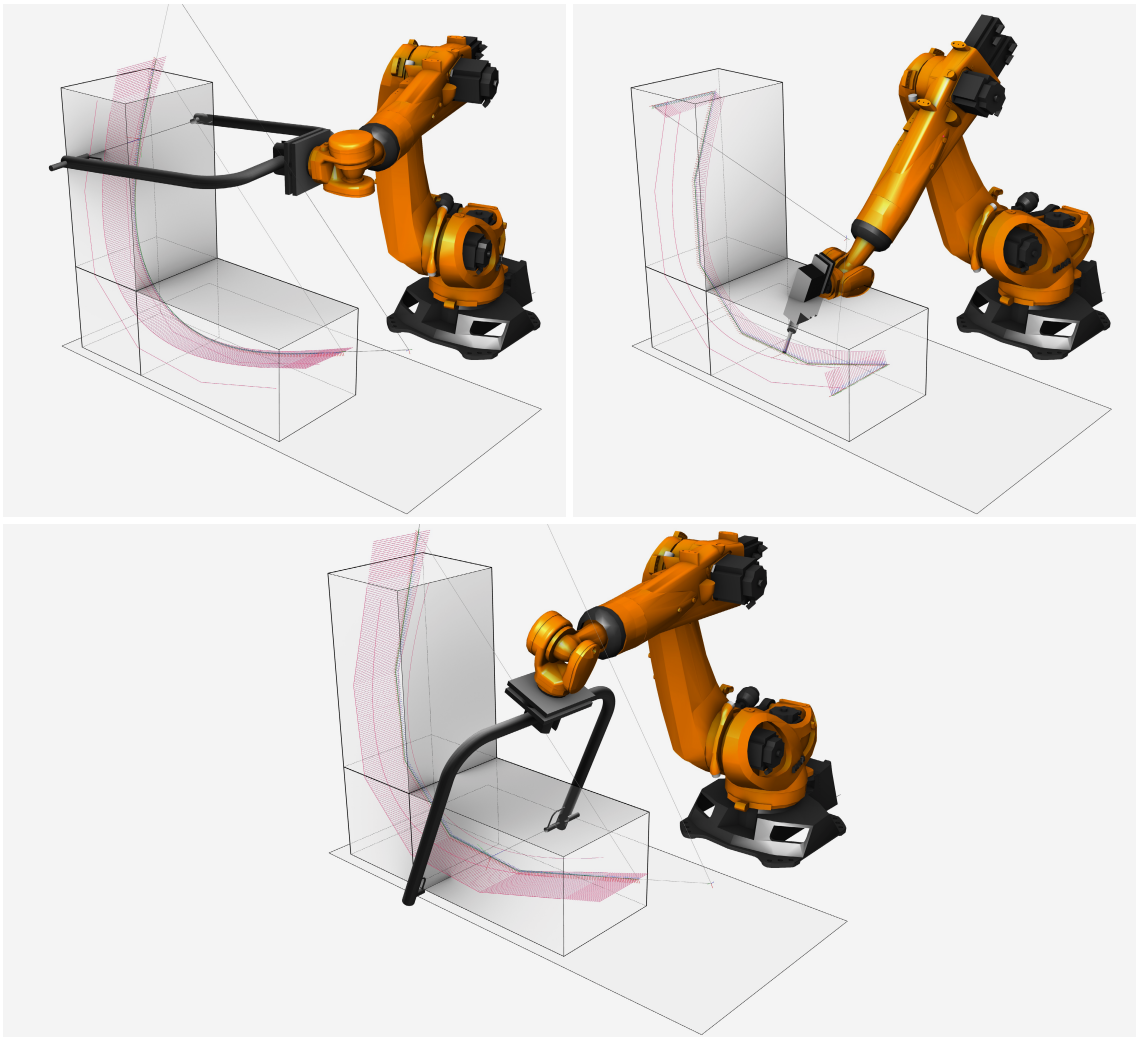


Figure 4.94: Toolpaths for mould half B1. a) interior surface; b) perimeter surface; c) exterior surface.

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mould, the top layer was not actually necessary, being only used for stacking and transportation purposes. Nevertheless, if needed, the process could have been further optimized to nest more moulds in the remaining EPS material. At this stage, the robotic fabrication phase proved to be a straightforward process, clearly adaptable for larger production scales, maintaining similar fabrication times and viability indicated by previous experiments.

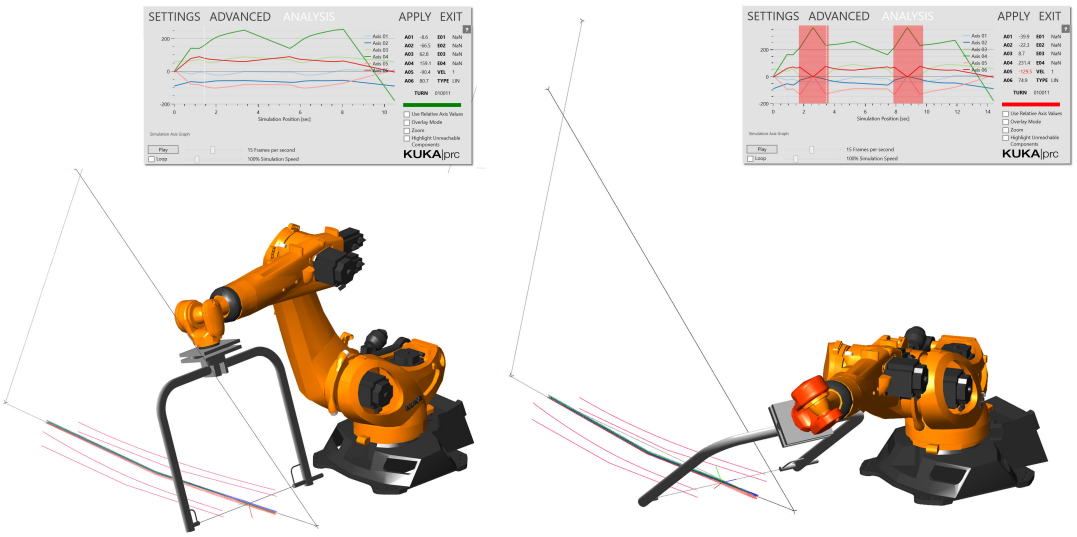


Figure 4.95: Tool path analysis and simulation for collision and reach checking in Kuka|PRC for Grasshopper for Rhinoceros. a) simulation without any conflicts; b) simulation with unreachable positions in red. (The difference in both is the position of the guide point used.)



Figure 4.96: Robotic fabrication steps for mould halves A and C: a) axis surface; b) interior surface; c) perimeter flank milling; d) exterior surface; e) core surface; f) finished mould parts (for interior surface); g) A1 mould parts; h) A1 and A2 mould parts before assembly.

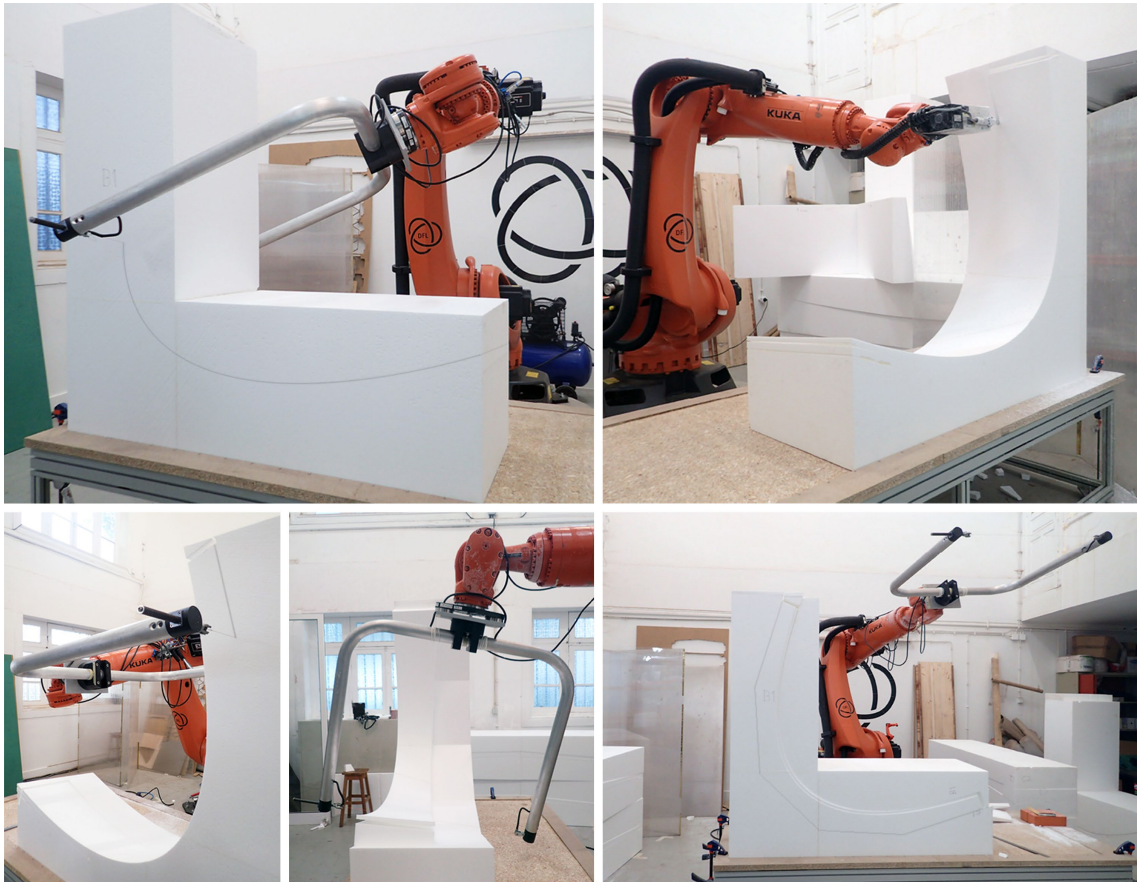


Figure 4.97: Main robotic fabrication steps for mould halves B: a) interior surface; b) perimeter flank milling; c) exterior surface; d) core surface; e) B1 finished mould parts.



Figure 4.98: Gluing process for the mould halves, interior and perimeter surface parts.

4.5.5 GRC fabrication

Parallel to the robotic fabrication of the final mould parts, and using a similar design, programming and materials, a scaled-down mould section was fabricated. This was conducted as trial run for some aspects of the robotic fabrication processes and also for the subsequent steps in the materialisation chain. Also, for early testing of the adequacy of the moulds for GRC production in the prefabrication environment and, in particular, the surface coatings of the EPS moulds. In this case, the mould surfaces were coated with polyurea,[15] granting it a much smoother texture than raw EPS. In the end, these results were not usable due to some resulting deformations, needing further material studies before application.

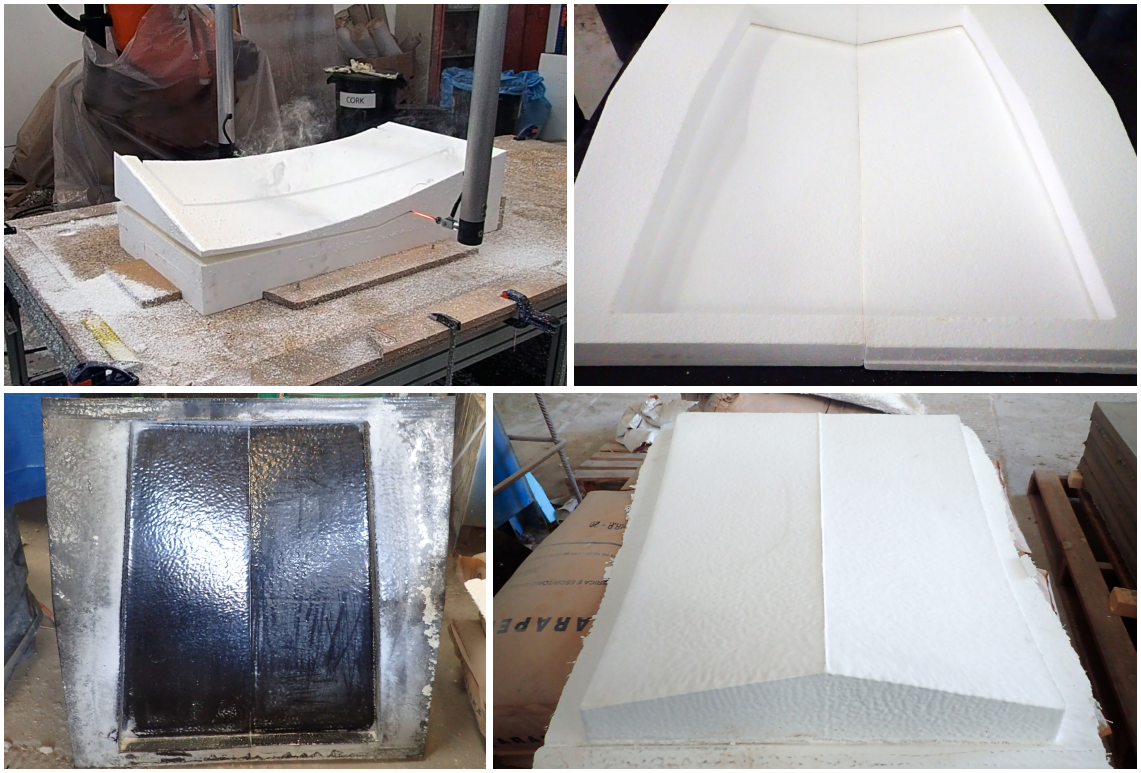


Figure 4.99: Preliminary test using a prototype scaled mould. a) robotic fabrication using a 2mm hot wire; b) mould surface before coating; c) polyurea coating; d) resulting GRC casting.

The final production of the GRC panels took place after the transportation of the three moulds to the precast facility of the project's industrial partner, Mota-Engil, S.A.. At this stage, preparatory steps were conducted on the mould before the actual GRC production process started. These included the application of an acrylic sealant to the interior edges of the mould and a

[15] Polyurea is a liquid synthetic polymer which is regularly used as waterproofing and can be used as coating for moulds, resulting in a hard, smooth surface.

simple coating of demoulding oil to the interior mould surfaces. Also, a set of metal anchor elements were inserted in the moulds, to be embedded in the GRC matrix. These metal fixings[16] (two on each connection surface between the three arch elements) served as fastening for all the arch elements in the final assembly (Figure 4.100).



Figure 4.100: Preliminary works in the moulds at the Mota-Engil precast facility: a) mould joint sealing; b) close-up of male fastener inserted in the EPS mould; c) mould A with metal fasteners; d) mould B with metal fasteners.

For the actual GRC spray process, a white pigmented mix was prepared to make a clear distinction between the two materials and to accentuate the geometric features of the arch. The GRC fabrication procedure consisted multiple manual stages. For each of the three panels, an initial surface layer was sprayed, without including any fibres (to prevent fibres in the apparent surfaces), followed by the spraying of the cement mix with added glass fibres. The GRC mix was then manually compacted with a roller ensuring the final thickness of 15mm. At this stage the metal fasteners were fitted and the core EPS parts were placed in the cavities. Finally, the

[16] The metal fasteners used were different for the side and arch apex parts. The first were composed of an embedded threaded nuts and an exterior threaded pin. These pins could then be inserted in 4 metal washers embedded in the 2 connecting surfaces of part B.

perimeter gaps and areas around the metal fixings were filled with GRC and smoothed, embedding all elements together. Two more threaded metal sleeves were also added to the back of the panels for ease of demoulding and transportation of the panels. After curing for 24 hours, the panels were easily demoulded, taking advantage of the anchor points for crane operations. Figure 4.101 and Figure 4.102 illustrate these steps in the GRC prefabrication of the Corkcrete Arch.



Figure 4.101: GRC production process for arch part A and C: a) surface layer (cement matrix only); b) main GRC spraying; c) manual edge profiling; d) manual roller compacting; e) placement of threaded nuts; f) placement of core EPS elements; g) spraying of perimeter gaps; h) compacting perimeter gaps; i) finished part while curing.



Figure 4.102: Main stages of the GRC production process for arch part B: a) moulds before casting in the precast facility; b) surface layer (cement matrix only); c) mould after main GRC spraying and compacting; d) placement of shaped EPS core halves; e) fixing of metal washers in bottom surfaces; f) placement of threaded nuts for transportation in apex section; g) spraying of perimeter gaps; h) hand shaping around inside of metal washers; i) finished part while curing.

As expected, the surface finishing quality of the GRC panels was not completely smooth. Because of the porosity of the EPS material, some its cellular texture was transferred to the finished surfaces, as well as traces of the original stock material joints. In the particular case of this prototype, a smoother surface texture was desired. Therefore, after demoulding, each part was manually sanded to remove the majority of these textural effects (Figure 4.103).

Throughout this stage of the process, it became clear that the robotically produced moulds were effortlessly used in the industrial setting of the precast facility by the workers. They proved to be suitable for regular spraying equipment, strategies and operating procedures without adaptations or special knowledge required, validating its usage in this environment.



Figure 4.103: Post-processing of the arch GRC components: a),b) general view of arch part; c) close-up of surface texture before sanding; d) manual sanding process; e) final GRC surface texture.

4.5.6 Assembly and results

After the production of the GRC, the Corkcrete Arch was tested for manually assembly and verification of the results. These included testing of the metal fixing system and also the overall geometry of the panels. This initial GRC assembly, in comparison with the original 3D geom-



Figure 4.104: Finished GRC apex part at the prefabrication facility of Mota-Engil.

etry also provided further data for the final fabrication of the cork panels, which were milled to fit.[17] Nevertheless, small geometric deviations from the modeled geometry were found to be well inside construction tolerances and were easily absorbed in the construction joints of the arch system.

With final GRC and cork components fabricated, the final structure was again manually assembled several times, in different settings, without mechanical aid. This demonstrated the lightweight properties of the system and suggested the feasibility of expanding it for larger applications (Figure 4.105).



Figure 4.105: Manual assemblies of the Corkcrete Arch.

With the final assembly stages, in adequate lighting situations and with all parts in place, faint marks of the hot-wire could be found throughout the final surfaces of the GRC components as somewhat expected from previous experiments. These occurred in the main surfaces and with more emphasis in the more curved sections of the arch apex (Figure 4.104). Although uninten-

[17] This was done to achieve the best continuity possible between the GRC and cork materials and overcome any possible deformations from the casting or flexing of the GRC components in situ.

tional and generally undesired, in this particular case, due to their connection with the arch's intrinsic geometry, these textural elements added an interesting aesthetic layer as fingerprints of the rhwc process and reminders of the connection between design, technology and materiality developed in this work.

The following images present these final installation results of the Corkcrete Arch.



Figure 4.106: Corkcrete Arch installation, FAUP garden (Photo by Pedro Varela).



Figure 4.107: Corkcrete Arch, side view, FAUP garden (Photo by Pedro Varela).



Figure 4.108: Corkcrete Arch, detail of apex section, FAUP garden (Photo by Pedro Varela).

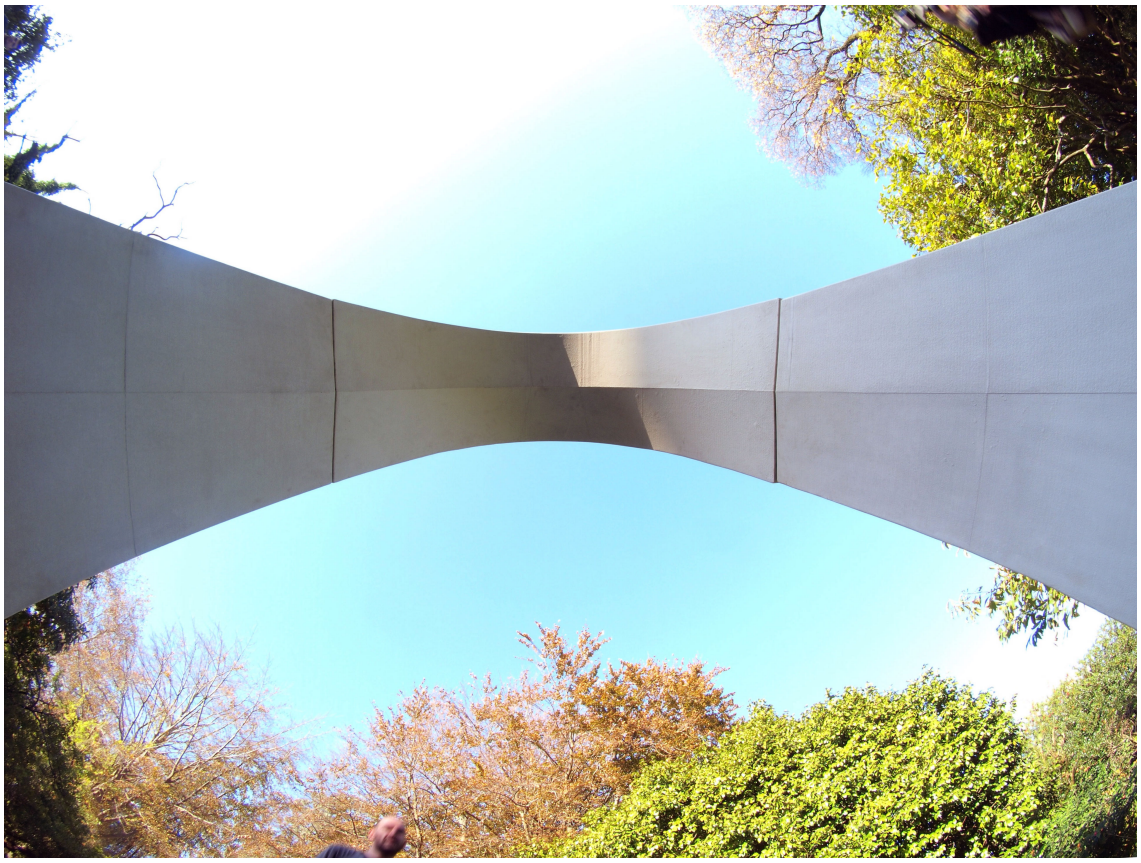


Figure 4.109: Corkcrete Arch, view of interior GRC surface, FAUP garden (Photo by Pedro Varela).



Figure 4.110: Corkcrete Arch, general view, FAUP patio (Photo by Pedro Varela).

4.5.7 Conclusions

From a technical standpoint, the GRC elements for the Corkcrete Arch project demonstrated the flexibility and versatility of the use of robots when compared with traditional CNC systems, being able to deploy different digital fabrication processes (RHWC and 3D milling) optimizing their inherent constraints. Furthermore, the revised layered mould strategy proved a viable solution for the production of complex moulds within the limitations of robotic hot-wire cutting. The time and cost-efficient nature of this process and its validation in an industrial setting promoted the interest of the precast industry in continuing the research into this topic.

From a more general methodological standpoint, the work developed in the production of this work, not only validated strategies, but also allowed for the creation of a clearer picture of the full design to materialization process for such digitally empowered solutions. A complex process composed of several stages, with the interplay of digital design, digital fabrication, manual and industrial activities. Figure 4.111 traces an expanded view of the initial diagram presented in the beginning of this chapter illustrating all stages and key aspects that were found from design to fabrication of the Corkcrete Arch.

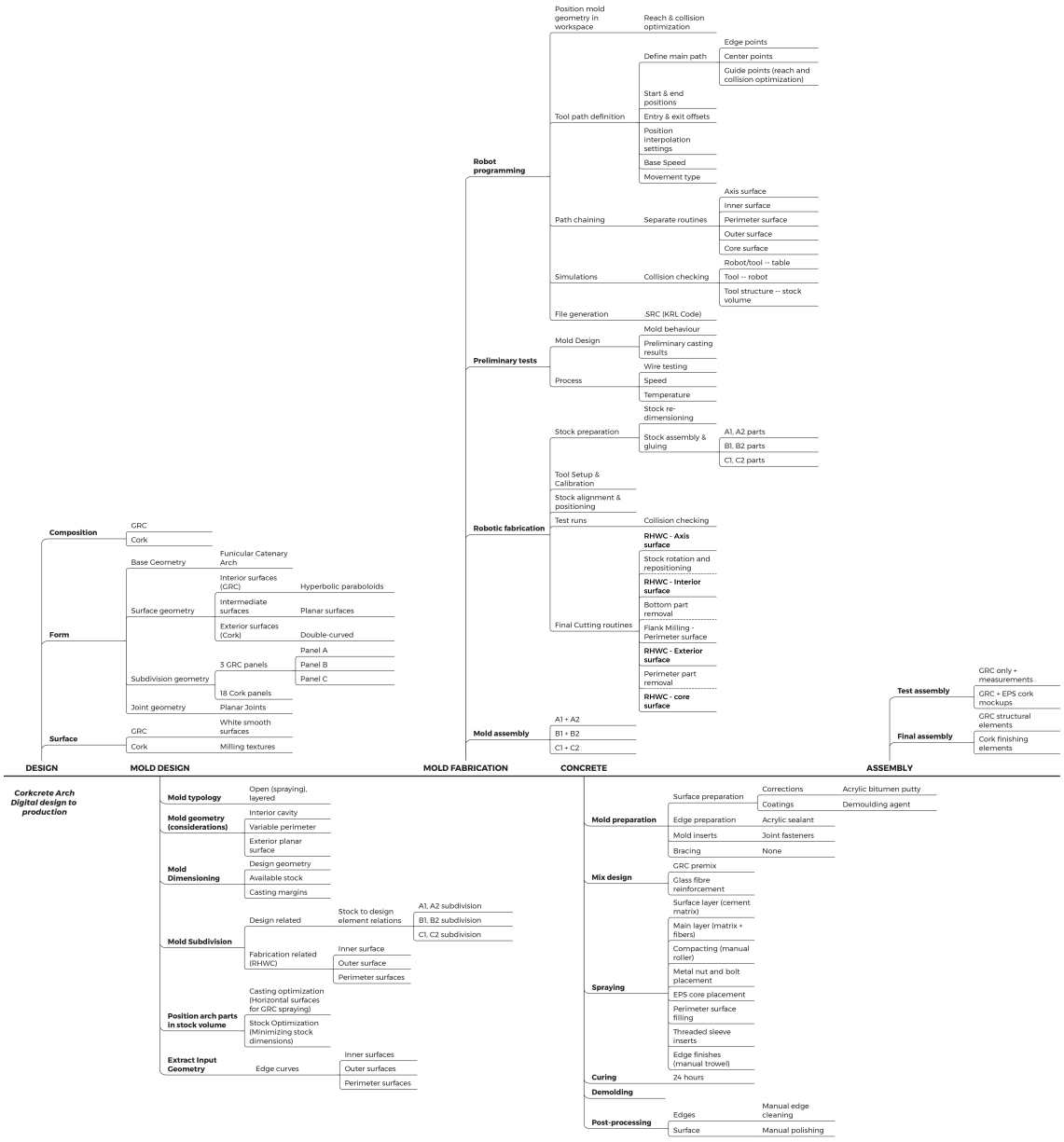


Figure 4.111: Expanded design to fabrication workflow for the Corkcrete Arch prototype.

4.6 Summary

In the scope of the thesis, this chapter corresponded to the main experimental part of the dissertation. It presented and discussed the results for a set of four prototypes developed for the exploration of different key aspects of RHWC and its application in complex architectural designs. Through this practical approach, several topics, processes and methods were developed that aimed to present an extended and multifaceted view of the architectural potential of this technology.

Such topics included the basic geometrical concepts for designing with ruled surfaces; a base digital workflow for working with RHWC and processes for generating input geometry and data for robotic control and fabrication; a characterization of the main geometric and procedural features of RHWC in comparison with 3D milling; innovative strategies for mould design and fabrication tailored for RHWC and complex geometries; potential avenues for expanding form, surface and composition in concrete; strategies for surface subdivision and fabrication through RHWC, tailored for material optimization; methods for design and prefabrication of lightweight panelling systems; validation of a complete workflow for the digital design and fabrication of such systems in industrial settings.

Chapter 5

Conclusion

At its beginning, this thesis presented a general research question: "*How can digital fabrication technologies expand the lexicon of traditional architecture in concrete, maintaining or expanding the traditional tectonic concepts of architecture in this material, through accessible and environmentally sustainable processes.*

Towards this objective, it was first necessary to establish a theoretical background that could enable an understanding of the particular character of concrete in an architectural context. From a review of literature in Chapter 2 - Concrete and Architecture (chapter 2), a theoretical framework was established through the reconstruction of the concepts of Form, Surface and Composition as the main dimensions in the tectonics of concrete architecture. Through the lens of these three dimensions and a review of historical examples of concrete architecture, different recurring themes could be found that presented possible avenues for expansion in a digital context. Complex curved forms and precast modular components, surface formwork traces and other textural effects, performative and aesthetic material compositions were found to be such avenues.

It was also understood that in many cases, traditional formwork fabrication processes imposed substantial difficulties to such expressive solutions in concrete, and that such difficulties still have translations to contemporary practices. Thus, from this analysis, it is understood that new transformation technologies - digital fabrication - can overcome some of these limitations and provide this expansion of concrete architecture.

Current industrial practices reveal the use of a key set of established digital fabrication technologies for concrete architecture. Nevertheless, there are a multitude of digital fabrication solutions in current research in academia. To understand this new digital context, in Chapter

3 - Digital Transformations (chapter 3), we conducted a large survey of approximately 100 cases of the use of digital fabrication in concrete, from research and practice. This survey enabled the creation of a classification system, starting from a main departure point in their application directly in concrete fabrication or in formwork fabrication. This systematic approach allowed for the characterization of each family of processes and the realisation of their strengths and weaknesses as well as comparing them with the previously established conceptual framework. It was found that by mapping current examples of concrete architecture empowered through digital fabrication technologies to this framework of form, surface and composition, a thematic continuity in the expression of this material could be found. As a whole, digital fabrication processes seemingly enabled an expansion of the language of concrete, not in contrast, but in line with traditional concepts of form, surface and composition. This link could be found in the recurring thematics of complex curved freeforms; variable modular systems; digital process-specific formal vocabularies; process-driven and artificially superimposed surface textures of high resolution; digitally controlled material composition.

From this survey, classification and comparison, it was also concluded that although mainstream digital fabrication processes such as CNC formwork milling and 3D printing already present relevant advantages to more traditional processes, there are still critical difficulties in their application in practice which validate the need to find other suitable processes. These issues are mainly related with the balance between formal freedom and material sustainability, fabrication times and corresponding production costs and the availability and difficulty of adoption of these processes in practice. It was concluded that from the wide array of processes studied, Robotic Hot Wire Cutting could be presented as a viable and tectonically relevant digital fabrication technology for concrete architecture. Particularly by featuring a more balanced relation between geometrical freedom and material optimization, with the intrinsic vocabulary of ruled surfaces, while simultaneously presenting an important practical viability with large reductions in construction times and costs.

These assertions put forth the need for a practical exploration of the applicability of RHWC, for concrete construction which was conducted in Chapter 4 - Material explorations (chapter 4). The prototypes described in the four main experiments present in this chapter, allowed for a characterization of RHWC and its consideration as a viable digital fabrication strategy for concrete. By testing RHWC in the realisation of architectural prototypes, focusing in different aspects of the design and materialization of complex geometries in concrete, it was possible to ascertain its efficiency in terms of speed, material optimization and precision in describing continuous curved surfaces. Simultaneously, these experiments allowed for the understanding

of the relation of this specific digital process with the three tectonic signifiers studied. Namely, the particular formal lexicon of RHWC as an expansion of the ruled geometry subset with the added flexibility of robotic systems, the procedural traces of hot wire cutting and the use of EPS moulds as well as the possibility of working with multiple materiality by layering different concrete compositions.

Capitalizing on these possibilities, new processes and formwork systems were developed, tailored for the design and materialization of lightweight, thin shell concrete structures. Throughout the works developed, these were tested in different setups, concluding in a full-scale prototype, the Corkcrete Arch, which not only validated RHWC in a complete digital workflow materialized in an industrial context, but also can be put forth as one possible answer to the research question of this thesis. In effect, by simultaneously exploring formal, material and procedural implications of one technological tool and applying such knowledge to a bottom up design process, the expansion of concrete architecture can in fact be brought about by digital fabrication tools and that this expansion can effectively result in relevant architectural solutions.

5.1 Contributions

5.1.1 To the general field of digital fabrication

Applications of digital fabrication technologies within the realm of architecture constitute a vast and continuously evolving domain. In the particular case of concrete architecture, the panorama of available digital fabrication solutions in current established practice and at the forefront of scientific research is usually dominated by few processes. This reality obscures the fact that a much wider array of digitally enabled fabrication processes can present interesting and relevant solutions for materialising concrete architecture.

Thus, towards the understanding of the breath of digital fabrication processes for concrete architecture, the main contribution of this thesis is the development of a classification system and analysis of examples, creating a wide overview of this field. This classification system featured:

- The survey of approximately 100 different examples of applications of digital fabrication technologies for the production of concrete architectural elements.
- A tree structure, separating examples into a hierarchy of families, identifying 13 main dig-

ital fabrication strategies for concrete architecture, from this initial universe, further subdivided into 24 different technological applications.

- An open and understandable classification system by using at its base, known material transformation logics - subtractive, formative and additive processes, which is expandable in a foreseeable future.

Although it will evidently be an incomplete list, as new examples and processes emerge constantly, this systematization enables a current and complete summary of digital fabrication solutions for concrete, structuring this area of knowledge and allowing for clearer comparative studies. Furthermore, it also sets up a framework for finding and understanding future possibilities in an expanded context of solutions.

5.1.2 To robotic hot wire cutting for concrete

As was described in Chapter 2 - Concrete and Architecture, the creation of complex freeforms has been one of the main signifiers of concrete architecture both in traditional and current examples. It was also shown that traditional formwork fabrication methods for concrete, particularly wood formwork systems, impose difficulties in this regard, with geometric, time and cost limitations. Considering that most of these systems are still in use today, and such issues still arise, digital fabrication strategies present a key opportunity to overcome such materialization challenges in concrete. As was shown in Chapter 3 - Digital Transformations, some of the most common digital fabrication strategies for concrete architecture, namely 3D milling of formwork and the emerging field of direct 3D printing of concrete through extrusion, also present issues for their widespread adoption.

In this regard, the main practical contribution of this thesis is the demonstration of the validity of Robotic Hot Wire Cutting as an alternative strategy for the creation of complex concrete architectural elements, shown in Chapter 4 - Material explorations. Towards this, several contributions were made:

- The characterization of RHWC and its geometric limits and the development of strategies for the design of ruled surfaces feasible through RHWC.

- The development and experimental testing of a layered mould design and fabrication method, specifically tailored for RHWC, overcoming the main limitation of creating cavities through wire cutting.
- This mould system enabled the design and materialisation of curved panels of ruled geometry, with variable perimeter boundaries.
- It also allows for interior subdivisions which enable different layers of materiality, without substantially increasing mould complexity and fabrication times.

The revision of the layered mould system and its simplification opened the possibility of greatly optimizing RHWC for material usage, waste generation and fabrication times, in specific design situations. This contributed to the further development of the sustainability of this digital fabrication process, resulting in:

- A solution for optimized material usage in concrete panelling sytems for ruled surfaces, consisting of a surface tessellation strategy and a battery mould system.
- A method for tessellating surfaces through projection, enabling the generation of panels with equal boundary geometry that can be place inside a regular stock volume.
- A corresponding design for a formwork system and digital fabrication process which enables its materialization through sequential slices of a single stock volume.
- The illustration and exploration of this process through its application to a known example of historical reference, the Philips Pavilion.

Finally, the Corkcrete Arch was developed as a final, multi-purpose prototype, demonstrating the design possibilities of ruled surfaces in this context as well as testing RHWC in for the creation of complex GRC components, in an industrial prefabrication setting. In this specific context, several contributions were made concerning the design and fabrication of the Corkcrete Arch:

- The development of a multi-material, lightweight panelling system, using GRC and cork, with the ability to define light, self-supporting structures.
- The adoption of the previous layered mould system to take advantage of the use of multiple digital fabrication systems, specifically RHWC and milling, maximizing the potential of each process.

- The validation of the complete digital design to fabrication process, for the production of a full scale self-supporting architectural prototype, including its testing in a prefabrication industrial setting, involving manual and robotic processes.

As a final note, regarding our contributions. The work developed here contributed for laying the first groundwork for the use of RHWC for architectural concrete in Portugal. At a national level, it represented some of, if not the the first experiments towards this objective which have, in the mean time, resulted in the execution of more ambitious projects. Although outside of the scope of this thesis, the recent execution of the large-scale GRC canopy structure in a luxury hotel in the south of Portugal was developed in succession of the work presented here. In this regard, we can consider that, its materialization represents not only the proof that this area of research keeps advancing, but also in a very practical sense, validates the pertinence of this work.

5.2 Future work

As mentioned before, the classification system for digital fabrication solutions in concrete, presented in Chapter 3 - Digital Transformations (chapter 3), was created and populated with a limited set of examples, mainly derived from academic publications. This fact makes it, by nature, an incomplete list which in a future iteration could be populated with new branches as new strategies or variations develop. In this sense, to continue this work and increase the usefulness of such a system outside the scope of this thesis, it would be relevant to transpose this system into an open-access database of categorized digital concrete fabrication examples. Categorized databases of buildings already exist (e.g. Structurae, ArchInForm), but are commonly focused on categorising building typologies, strucutural typologies and materials, but no such database was found, focusing on architectural examples enabled by digital fabrication solutions. As this information is often diffuse and new research is often done in comparison with existing solutions, such database would be relevant in aiding current research in this field, collating academic prototypes and buildings materialised through innovative digital fabrication strategies. Such a database, could also be expanded for other architectural materials, using the same categorisation system.

In terms of methodology, one difficulty realised throughout the development of the practical experiments of this work in the robotic programming stages was the accurate visualization of RHWC paths and their end effects. In this regard, the resulting cutting surfaces not always corresponded to initial input surfaces and unexpected results could also occur at the intersection of these cutting planes and stock volumes. More so, if multiple cuts were considered. Although all necessary visualisations were created in the parametric environment used, this was also a cumbersome and slow process. Therefore, a possible research avenue would be the creation of a dedicated RHWC visualization tool. Such a tool could provide quick and accurate simulations, of resulting ruled surfaces considering specific cutting end-effectors. This could be relevant not only in production environments but also for academic experimentation and design.

Regarding the works developed this dissertation, multiple research lines were explored, resulting in the successful materialization of various prototypes. Nevertheless, considering the scope of each, they also unveiled a multitude of unexplored avenues which could be pursued in future research. From these possible avenues, a few can be highlighted:

The multimateriality studied in the case of the MSE panel experiment was merely indicative

of this possibility, with no actual performative function. Other processes such as 3D printing already deal with the possibility of continuous variations of composition. Nevertheless the presented layered composition could be an interesting low-tech alternative. As such, it would benefit from further research in more complete architectural applications which could also consider the possibility of added material performance. For instance, the notion of interior-exterior differences in an architectural envelope could be explored as well as other concrete compositions with added behaviours, such as thermal or acoustic insulation.

The design and materialization strategy developed for the Philips Pavilion reconstruction featured several constrains: the need for equal boundary shapes and the need for these boundary shapes to be projected in the same direction throughout each surface. This would eventually lead to difficulties in its application for surfaces with large curvature variations. A possible solution for this issue which was pointed but not developed would be the use of mould stacks with variable shapes.

In the development of the GRC+cork panels for the Corkcrete Arch prototype, some concessions were made in the interest of simplification and ease of assembly for the multiple situations it was presented. One such concession was that the cork materials were not fully integrated with the GRC system. Therefore, a more simple and complete system could be the future development of this research. One such application would be the creation of a lightweight sandwich GRC self-supporting panel system with a double sided finishing and an interior insulation core, tailored for variable curved geometries.

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Appendices

Annex A

This section presents the examples analysed for the creation and population of the categorisation system presented in Chapter 3 - Digital fabrication Processes (section 3.1).

Project Name	Year	Project Type	Construction Type	1. I. Mode	2. T. Logic	3. D.F. Technology	4. Application
Zollhof Towers	1999	Architectural	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
Big Belt House	1999	Architectural	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
Contour Crafting	2004	Research	Prefabricated / In-situ	Direct	Additive	3D Concrete Printing	Extruded concrete
Mercedes Benz Museum	2006	Architectural	In-situ	Indirect	Subtractive	2D Cutting	Wood formwork
Spencer Dock Bridge	2008	Architectural	In-situ	Indirect	Subtractive	3D Milling	EPS molds
Ruled Staircase	2008	Architectural	In-situ	Indirect	Subtractive	3D Cutting	EPS molds
WINSUN 3D printing	2008	Commercial	Prefabricated / In-situ	Direct	Additive	3D Concrete Printing	Extruded concrete
Freeform Construction	2008	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Radiolara Pavilion	2008	Commercial	Prefabricated	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
Rolex Learning Center	2009	Architectural	In-situ	Indirect	Subtractive	2D Cutting	Wood formwork
O14 Tower	2010	Architectural	In-situ	Indirect	Subtractive	3D Milling	EPS molds
Pinch wall	2010	Research	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds (plaster casting)
Roca London Showroom	2011	Architectural	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
ADAPA Concrete Panels	2011	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Molding Table
Unikabeton	2011	Research	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
Robotic Clay printing	2011	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Clay mold
Variable Density concrete	2011	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Seat Slug	2011	Architectural	Prefabricated	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
Slazburg Building Academy	2012	Architectural	In-situ	Indirect	Subtractive	3D Milling	EPS molds
Fatty Shell	2012	Research	Prefabricated	Indirect	Subtractive	2D Cutting	Fabric molds
Pre-Vault	2012	Research	Prefabricated	Indirect	Subtractive	2D Cutting	Plastic molds
Cast Thicket	2012	Research	Prefabricated	Indirect	Subtractive	2D Cutting	Plastic molds
Robotic Casting	2012	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Robotic Mold
AAC Voussoir Assembly	2012	Research	Prefabricated	Direct	Subtractive	3D Concrete Cutting	Diamond Wire Cutting
P_ball	2012	Prototype	Prefabricated	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
Louisiana State Museum	2013	Architectural	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
Boston Harbour Park Pavilion	2013	Architectural	In-situ	Indirect	Subtractive	2D Cutting	Wood formwork
Crease Fold Pour	2013	Research	Prefabricated	Indirect	Subtractive	2D Cutting	Plastic molds
Tailorcrete Demonstrator	2014	Research	In-situ	Indirect	Subtractive	3D Milling	EPS molds
Tailorcrete Panels	2014	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Wax molds
Smart Dynamic Casting	2014	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Robotic Mold
Freefab Wax Formwork	2014	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Wax extrusion mold
Meshmould prototype	2014	Research	In-situ	Indirect	Additive	3D Printed Molds	Plastic mesh extrusion
Branch Technology	2014	Research	In-situ	Indirect	Additive	3D Printed Molds	Plastic mesh extrusion
UHPC sand molds	2014	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Binder Jetting sand mold
Relaxed Vault	2014	Research	Prefabricated	Direct	Subtractive	3D Concrete Cutting	Water Jet Cutting
Total Kustom 3D printing	2014	Commercial	Prefabricated / In-situ	Direct	Additive	3D Concrete Printing	Extruded concrete
DSHAPE Lunar Outpost	2014	Research	In-situ	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
Round Room	2014	Research	Prefabricated	Direct	Subtractive	2D Concrete Cutting	Cut AAC blocks
Resolution Wall	2014	Research	Prefabricated	Direct	Additive	Robotic Assembly	Assembled concrete components
Salermo Maritime Terminal	2015	Architectural	In-situ	Indirect	Subtractive	3D Milling	EPS molds
Odico Kirk Kapital Building	2015	Architectural	In-situ	Indirect	Subtractive	3D Cutting	EPS molds
Waal Bridge Extension	2015	Architectural	In-situ	Indirect	Subtractive	2D Cutting	Wood formwork
House of Dior Seul	2015	Architectural	Prefabricated	Indirect	Subtractive	2D Cutting	Wood formwork
Microtherme	2015	Research	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
Bloom Pavilion	2015	Prototype	Prefabricated	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
WASP 3D Printed Beam	2015	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
National Veterans Museum	2016	Architectural	In-situ	Indirect	Subtractive	2D Cutting	Wood formwork
Topology Optimized Slab	2016	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Binder Jetting sand mold
Cast on Cast	2016	Research	Prefabricated	Indirect	Subtractive	2D Cutting	Wood formwork
Spatial Wire Cutting	2016	Research	Prefabricated / In-situ	Indirect	Subtractive	3D Cutting	Hot Blade mold cutting (EPS)
3D printed Bridge in Alcobendas	2016	Architectural	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete

Project Name	Year	Type	Construction	I. Mode	M. Logic	D.F. Strategy	Result
BRUIL Variable Color Concrete	2016	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
R&Drone Laboratory	2016	Architectural	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
CONPrint3D	2016	Research	In-situ	Direct	Additive	3D Concrete Printing	Extruded concrete
Precast Concrete Shells	2017	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Sand molds
Mars Pavilion	2017	Research	Prefabricated	Indirect	Formative	Formwork Molding	Fabric molds
Smart Slab	2017	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Binder Jetting mold
SkelETHon	2017	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
Digital Construction Platform	2017	Research	In-situ	Indirect	Additive	3D Printed Molds	PU Extrusion Mold
Meshmould in-situ fabricator	2017	Research	In-situ	Indirect	Additive	3D Printed Molds	Plastic mesh extrusion
Freeform GRC Panels	2017	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic mesh extrusion
Xtree Column	2017	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Cement Extrusion Mold
Kuwait Airport Expansion	2017	Architectural	Prefabricated	Indirect	Formative	Dynamic Molds	Molding Table
Hedracrete	2017	Research	Prefabricated	Indirect	Subtractive	3D Milling	EPS molds
3D printed Bridge Eindhoven	2017	Architectural	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
3D Printed Reinforced Beam	2017	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Particle Bed Concrete Printing
APIS COR 3D Printed House	2017	Architectural	In-situ	Direct	Additive	3D Concrete Printing	Extruded concrete
HINDCON	2017	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Xtree Woven Benches	2017	Prototype	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Cyclopean Cannibalism	2017	Research	Prefabricated	Direct	Subtractive	3D Concrete Milling	Milled concrete
Odico Opticut Prototype	2018	Research	Prefabricated	Indirect	Subtractive	3D Cutting	EPS molds
Smart Dynamic Casting	2018	Research	Prefabricated	Indirect	Formative	Dynamic Molds	Robotic Mold
Sika 3D Printed Moulds	2018	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
BASF 3D Printed Moulds	2018	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
Smart Concrete wall	2018	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
Confluence Park	2018	Architectural	In-situ	Indirect	Subtractive	3D Milling	Fiberglass molds from EPS positives
Lotus House	2018	Architectural	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
SC3P Shotcrete 3D printing	2018	Research	Prefabricated / In-situ	Direct	Additive	3D Concrete Printing	Sprayed Concrete
Swarm Printing	2018	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Triple S	2018	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Profile 3D Printing	2018	Research	Prefabricated	Direct	formative	Robotic Concrete Molding	Molded concrete
Stuttgart 21 Parabolic Arch	2019	Architectural	In-situ	Indirect	Subtractive	3D Milling	Wood formwork
Staircase	2019	Architectural	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
DE|Stress Pavilion	2019	Prototype	Prefabricated	Indirect	Formative	Formwork Molding	Clay mold
Red Brick Pavilion	2019	Prototype	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold for brick structure
Eggshell	2019	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Plastic extrusion mold
Knit Candela	2019	Research	Prefabricated	Indirect	Additive	CNC knitting	Fabric molds
Baoshan Pedestrian Bridge	2019	Architectural	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Concrete Choreography	2019	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
DE|Stress Pavilion	2019	Research	Prefabricated	Direct	Additive	3D Concrete Printing	Extruded concrete
Ribbed concrete slab	2020	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Cement Extrusion Mold
Lightweight Concrete Ceiling	2020	Research	Prefabricated	Indirect	Additive	3D Printed Molds	Cement
Little Island	2020	Architectural	In-situ	Indirect	Subtractive	3D Milling	EPS molds
House #5 David Leggett	2020	Architectural	In-situ	Indirect	Subtractive	3D milling	Wood formwork
"Stay-in-place" Concrete	2020	Research	Prefabricated	Direct	Additive	Robotic Assembly	Assembled concrete components

Table 1: Table of examples studied to organize the different strategies for integration of digital fabrication in concrete architecture, both in architectural practice and research between 1999 and 2020.

Annex B

This section presents relevant published papers that were produced during the development of this thesis. They represented key moments in the dissertation as they not only validated the work developed, but also presented opportunities for discussion and further advancement. They are presented here in their original form and correspondence with the thesis' structure can be viewed in Figure 1.

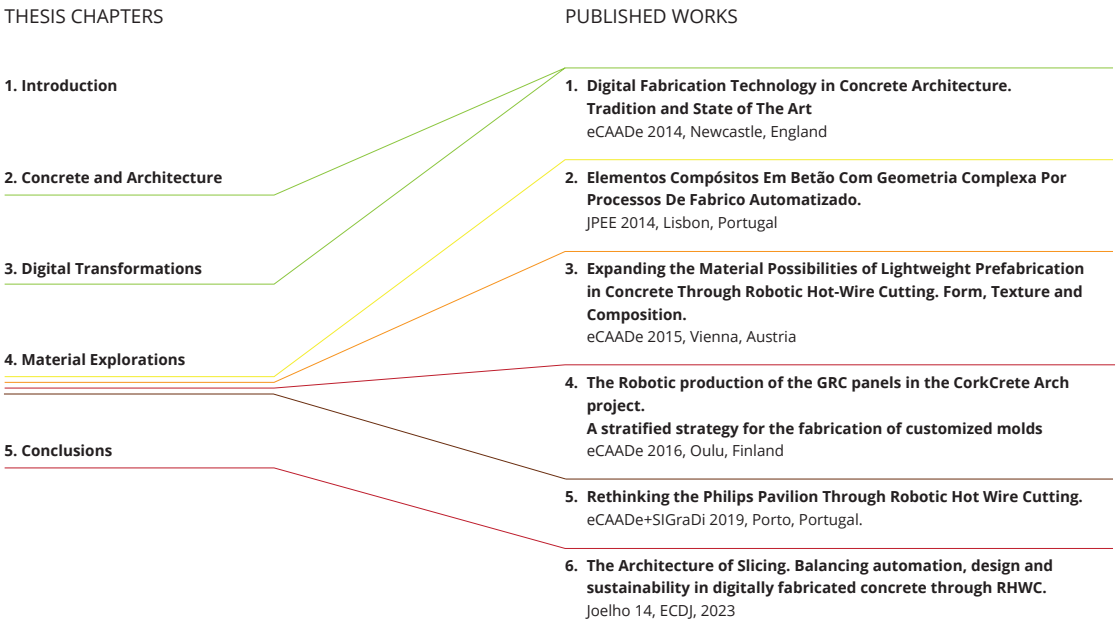


Figure 1: Published papers during dissertation development in relation with thesis chapters.

Martins, P. and Sousa, J. (2014): "Digital Fabrication Technology in Concrete Architecture" in Thompson, Emine Mine (ed.), Fusion - Proceedings of the 32nd eCAADe Conference - Volume 1, Department of Architecture and Built Environment, Faculty of Engineering and Environment, Newcastle upon Tyne, England, UK, 10-12 September 2014, pp. 475-484.

Carvalho, P., Nunes, S., Sousa, J. (2014): "Elementos Compósitos em Betão com Geometria Complexa por Processos de Fabrico Automatizado" in 5as Jornadas Portuguesas de Engenharia de Estruturas, 26 a 28 Novembro 2014, LNEC, Lisboa, Portugal.

Martins, P.; Campos, P., Nunes, S. and Sousa, J. (2015): "Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting - Form, Texture

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Digital Fabrication Technology in Concrete Architecture

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Technological innovation has been an important driving force in architecture, enabling and inspiring architects and engineers by giving them new tools for solving existing problems. In the last two decades, the exploration of digital design and fabrication technologies has stimulated the development of a variety of interests and strategies to materialize increasingly complex and customized solutions in architecture, with traditional building materials.Reinforced concrete is the most widely used material in the building industry today and throughout its history has been the subject of vast research into its performance as a construction material and its tectonic potential in architecture. As such, the introduction of digital fabrication processes in concrete construction represents the biggest prospect for renovation of our built environment and at the same time, presents particular difficulties and opportunities, which are now being addressed. In an effort to investigate the alternative design and material possibilities in concrete emerging from the use of digital fabrication technologies in architecture, this paper proposes a focused view of digital fabrication applied to concrete construction with two areas of research. By framing the research in the context of reference works in concrete architecture of the 20th century, this paper describes and illustrates taxonomy of existing and possible types of integration of digital fabrication technologies in concrete architecture in the realms of Practice and Research.This characterization allows the authors to frame the relation between material, technology and architecture in different environments regarding the same material, extracting a clear image of existing processes, their potential and shortcomings, as well as expectations for future developments.

Keywords: *Digital Fabrication, Concrete, CAM, Robotics, Sustainability*

INTRODUCTION

Since the rediscovery of roman concrete and the invention of reinforced concrete in the nineteenth century, concrete has been the focus of continuous technological advances, driving with it an expectation for new architectural possibilities.

Reinforced concrete is a compound material composed of two elements: the cementitious matrix and the reinforcement. It can thus be considered a hybrid material, which combines the properties of its

constituents to achieve a different set of characteristics. This hybrid nature, which is further characterized by a duality of states (i.e. evolving from liquid to solid) through a mould, has been at the core of contemporary discussion about the intrinsic plasticity of this material in architecture. For instance, Forty (2006) suggests the idea of understanding concrete as a process rather than solely as a material. Indeed, its rich and diverse history of technological innovations through research and practice has prevented concrete to have a fixed underlying traditional and accepted aesthetics.

This multi-faceted background of a material has provided a fertile ground for exploration for new materialities. This has become increasingly relevant in the last decades, with the dissemination of the emerging digital design and manufacturing technologies (CAD/CAM). Together, they have inspired a growing interest in rethinking concrete, while helping and builders to bridge the gap between design and construction. In this context, the subject of this paper is to investigate and outline the emergent opportunities for concrete architecture that have been supported by the use of digital fabrication processes.

HISTORICAL PERSPECTIVE

As a starting point it is important to contextualize this subject by examining some innovative examples in the history of concrete architecture. Past architects and engineers have produced relevant works in concrete, which have been a source of inspiration for those who are trying to innovate the application of this material in architecture.

Thus, the following themes were selected to set a framework to analyse the reference works of concrete architecture:

1. Complex Forms
2. Surface Textures
3. Material Composition

While form and surface are the basis of the majority of the examples surveyed, changes in the material composition of concrete have been used to improve its functional properties and to renew its aesthetic qualities.

In this context, this research contextualizes these traditional recurring themes to use them as a basis to analyse and characterize the recent 'digital' works.

Complex Forms. The first reinforced concrete prototypes, the concrete boat and conical vases of Lambot and Monier in 1848-50, exposed at an early age the opportunity of materializing complex forms in this material. Decades later, several geometrically appealing images of American silos and industrial buildings in concrete, were published by Walter Gropius in 1913 and re-used in Le Corbusier's manifesto of 1925, illustrating this early link between concrete and expressive forms in architecture.

Reinforced concrete made its way into architecture through the development of innovative construction systems (e.g. Hennebique system), which opened new spatial possibilities. However, it was its plastic properties of conforming to any shape that made it a prime material for exciting formal explorations, which were subsequently adopted by modernist architects as the medium for a new architecture.

In the first decades of the 20th century, architects and engineers seek to control the process of materializing concrete, testing the limits of its material, formal and aesthetic possibilities. Among the different types of buildings, the exploration of concrete forms was particularly relevant in the thin shell constructions. Pioneered in early 30s by architects and engineers like Eduardo Torroja, Felix Candela and Miguel Fisac, this type of constructions showcased the plasticity of concrete in assuming self-supporting and continuous curved surfaces of reduced thickness. The Zarzuela Hippodrome (1935), the Palmira Chapel (1959) or the Jorba Laboratories (1965) are some clear examples of that. In most cases, the complex geometries exhibited in these works were based on exploring and combining ruled surface geometries. One of the most notable cases is Felix Candela who spent most of his career working with hy-

perbolic paraboloid surfaces, which were carefully combined and adapted to a large set of architectural programmes (Garlock 2008). One particular aspect of these constructions was the fact that their formwork was built with rigid wooden planks following the same geometrical creation rules. This defined a direct relation between material behaviour, form and construction technology, which has become increasingly relevant in the contemporary concept of digital materiality (Gramazio and Kohler 2008).

Surface Texture. Although the previous works had implicit qualities regarding the expression of their skin, they were mainly concerned with the formal expression of concrete. In the second half of the 20th century, architects started to insist more with the surface finishing of their concrete constructions. Le Corbusier's "béton brut" experiments, in which concrete cast with rough wood boards was left bare, prompted an exploration into the possible aesthetic properties of exposed concrete. American architects, like Louis Khan Paul Rudolph or I.M. Pei, developed throughout the 60s numerous works where the exposed concrete skin was treated to achieve expressive qualities. In works such as the Yale Art Gallery (1953), the Art and Architecture Building (1963), the Everson Museum (1968) and the Jonas Salk Institute (1965) surfaces textures ranged from rough to smooth features. In these cases, texture resulted from the formwork design or by mechanical or manual post processing techniques (Legault 2005), achieving varying visual and tactile sensations with the same material by manipulating the properties of its finished surface. Another relevant example consisted in the experiments of Miguel Fisac with flexible formwork, where the integration of new technologies within the process of concrete creation introduced deep changes in the textural and visual properties.

From this scenario, one can extract the relevance of controlling the production process of concrete as a medium for achieving expressive surface textures and infer that changes to this process can impart new material qualities.

Composition. Although, when referring to the works discussed before, traditional literature focuses mostly on shape and surface texture, much of those defining features were dependant on a careful attention to its mixture composition. Going back to the notion of reinforced concrete as a hybrid material, where steel was incorporated into a matrix of cement, sand and gravel, it is possible to understand the opportunity and potential of changing the composition of concrete. For instance, most of the works of Pier Luigi Nervi, like the Sports Palace in Rome (1958), featured a structural and formal complexity that was made possible by his research into the composition (i.e. reinforcement) of concrete and the subsequent development of ferroconcrete (Iori and Poretti 2005). Moving from the structural to the aesthetic properties, the composition of concrete has also been explored to achieve different visual expressions. Forty (2012) mentions Perret's careful selection of aggregates by their colour to feature in exposed concrete, while Legault (2006) mentions the case of Pei's use of selected mineral additives to achieve white or earth coloured surfaces in his projects.

The works described in this survey, suggest relevant clues to understand the possibilities that concrete construction can follow through digital fabrication. Nevertheless, they also reveal some of the greatest problems of materializing expressive works in concrete. As it was already discussed, formwork played a major role in the characteristics of the material and in the building process. Formwork construction conveyed a large part of expenditures in materials, labour and assembly time. Moreover, the particular types of formwork traditionally available (timber and, later, steel) introduce significant geometrical constraints on possible forms and undifferentiated repetition in most concrete constructions, which can only be partly overcome with additional building time and costs. Also, relevant efforts were put into achieving desired surface finishes through the careful control of the formwork materials and building processes, as well as by means of controlling the mixture of its components. However, these in-

terventions were still tied to the standardization constraints of the industry.

In this context, the recent use of digital fabrication technologies have started to tackle some of these constraints, proposing new ways of materializing concrete and revisiting and further exploring traditional concepts of form, texture and composition in concrete architecture.

THE INTEGRATION OF DIGITAL FABRICATION IN CONCRETE ARCHITECTURE

To examine the integration of digital fabrication technologies in the production of concrete architecture this paper considers the realms of practice and research. While the first side testifies the real impact in the built environment of using such technologies, the second one indicates the tendencies that can shape the next innovative applications of concrete in architecture.

Analysis methodology. The first step of the analysis consisted in surveying existing literature on relevant built works in which digital fabrication played a key role in the materialization of concrete elements. A set of key examples was then selected to illustrate the spectrum of similar and diverse approaches that could sustain the proposal of a taxonomy of the digital fabrication strategies.

To construct this analysis, a structure based on three consecutive categories was defined to organize the studied works:

1. Intervention mode
2. Digital Fabrication Technology
3. Theme

Facing the existing landscape of digital fabrication technologies and the dual state of the material (i.e. liquid and solid), the (1) Intervention Mode topic comprises two possibilities - direct and indirect. This division separates the cases where digital fabrication technologies are directly employed over the building components in concrete, from those where they are applied to other elements, which will then, indirectly, affect the production of concrete elements. In the latter case, a further distinction is considered by considering the possibility of intervening in the formwork or in the reinforcement. Furthermore, because the production of formwork is the focus of the majority of the surveyed works, this topic had to be subdivided taking into account different strategies based on their materiality: rigid, flexible or dynamic.

The (2) Digital Fabrication topic was divided into subtractive (Table 1), additive and formative categories, as proposed by Branko Kolarevic (2003). These topics were then subdivided into the specific fabrication technologies in order to illustrate the differences within the same family of fabrication processes.

Finally, specific (3) Themes were identified to each example according to three key concepts in the materiality of concrete architecture: Form, Surface and Composition. Given that these three goals, or interests, can be found in the relevant historical examples, critical comparisons between past and current works can be developed.

Examining the developments in Practice

The use of digital fabrication technologies became, in the mid 1990's, a indirect solution to the problem of building complex geometry in concrete, by enabling the production of custom moulds. The ca-

INTERVENTION			DIGITAL FABRICATION		THEME	EXAMPLE	
Mode	*Object*	*Type*	*Process*	*Technology*		*Work*	*Author*
INDIRECT	FORMWORK	RIGID	SUBTRACTIVE	CNC MILLING	FORM	Big Belt House	William Massie
			SUBTRACTIVE	CNC MILLING	FORM	Der Neue Zollhof	Frank Gehry
			SUBTRACTIVE	CNC MILLING	FORM	Phaeno Science Center	Zaha Hadid
			SUBTRACTIVE	CNC MILLING	FORM	Spencer Dock Bridge	Amanda Levete
			SUBTRACTIVE	CNC CUTTING	FORM	EPFL Rolex Learning Center	SANAA
			SUBTRACTIVE	CNC CUTTING	FORM	Mercedes Benz Museum	UNStudio
			SUBTRACTIVE	CNC MILLING	FORM	0-14 Tower	Reiser+Umemoto

Table 1
Digital Fabrication in Concrete Architecture – Developments in Practice

pabilities of CNC (Computer Numerical Control) subtractive processes were employed in the production of complex formwork in EPS (Expanded Polystyrene Foam). This material proved to be capable of withstanding the forces of the casting process and at the same time, was sufficiently soft to be quickly and accurately milled into a complex surface, reducing fabrication costs. The Table 1 summarizes the analysis about the use of digital fabrication technologies in the production of concrete elements in architectural practice.

Early examples of this production strategy can be found in the Neue Zolhoff project in Dusseldorf, Germany (Gehry Partners, 2000) and the Big Belt House in Montana, USA (William Massie, 2000). In both cases, digital fabrication technologies were used in the production of precast structural components (beams and walls) with geometrical features difficult to achieve with traditional formwork systems. This condition allowed the architects to further explore the formal plasticity of concrete.

As seen in the Table, CNC milling of homogeneous materials dominates the production in practice of complex geometries in concrete. Recently, these processes were developed and scaled up to the construction site, overcoming the need for prefabrication. The Science Center in Wolfsburg, Germany (Zaha Hadid Architects, 2005) and The Spencer Dock Bridge in Dublin, Ireland (Future Systems / Amanda Levete, 2008) are exemplar in showing the intrinsic relation between the design geometry and the fabrication possibilities. In the Phaeno Science Center, a careful analysis and subdivision of the designed form into single-curved and doubly-curved parts was developed in order to be, respectively, constructed with standard wooden formwork and with milled EPS formwork (Kara 2008). This feature had an immediate impact on the surface finishing qualities, given that one can clearly identify the wooden textures for the ruled sections of the cones and the smooth surface in the doubly curved transition areas. The Spencer Dock Bridge goes further with the materialization of doubly curved surfaces. Using milled formwork in high-density EPS, the building was built in a continuous way by pouring concrete onsite.

Another application of CNC milling of EPS has been for the production of sculptural voids in concrete surfaces, as was the case of the O-14 Tower (Reiser+Umemoto 2007). At the same time, other recent built projects employed the same technologies for the production of non-standard formwork in wood. The Mercedes Benz Museum (UNStudio, 2006) and the Rolex Learning Center (SANAA, 2010), both featured curved surfaces in concrete that were achieved through the precise CNC cutting of planar plywood panels to compose the desired double-curved geometries.

Although in the mentioned works it is clear that the application of digital fabrication in the production of formwork has enabled exciting formal explorations in concrete, it is also revealing that new problems emerge from this condition.

One issue regards the surface smoothness. When comparing these processes to traditional wood or steel formwork in standard construction, smooth surfaces are much harder to achieve through the materials commonly used in milling than with the traditional standard sheet materials. Moreover, in terms of formal freedom, the CNC milling process has its own geometrical constraints, depending on the number of available movement axis and the size of formwork stock material.

Problems with sustainability are also inherent to subtractive processes. The gradual removal of material layers produces large amounts of waste material that are not easily reusable. For instance, in the specific case of milled EPS, the need to apply non-recyclable coating agents to achieve satisfactory surface finishes makes the recyclable process necessary quite unviable. Facing the scale and complexity of architectural construction, research in digital fabrication technologies and materials engineering is required to overcome these problems (Table 2).

INTERVENTION			DIGITAL FABRICATION			EXAMPLE	
Mode	*Object*	*Type*	*Process*	*Technology*	*Theme*	Work	Lead researcher
INDIRECT	FORMWORK	RIGID	SUBTRACTIVE	ROBOTIC HOTWIRE	FORM	Fisac Variations	Felix Raspall
				CNC MILLING	FORM/TEXTURE	Tailorcrete	Silvan Oesterle
				CNC CUTTING	FORM	Pre: Vault	Dave Pigram
		FLEXIBLE			FORM	Fatty Shell: Fabric Formwork	Dave Pigram
		DYNAMIC	ADDITIVE	3D PRINTING	FORM	Smart Dynamic Casting	Ena Lloret Kristensen
	REINFORCEMENT				COMPOSITION	Mesh-Mould	Norman Hack
			FORMATIVE	ROBOTIC BENDING	COMPOSITION	Tailorcrete	Jens Cortsen
DIRECT	BUILDING COMPONENT		SUBTRACTIVE	CNC CUTTING	FORM	[c]shape pavilion	Alan Dempsey
				ROBOTIC DIAMOND WIRE	FORM	Diamond-wire Cut Concrete	Wes Mcgee
			ADDITIVE	3D PRINTING	FORM	Freeform Construction	Richard Buswell
					FORM	Contour Crafting	Behrokh Khoshnevis
					COMPOSITION	Variable Density Concrete	Neri Oxman

Table 2
Digital Fabrication in Concrete Architecture – Developments in Research

Examining the Developments in Research

The academia has been increasingly active in investigating the use of digital fabrication technologies in the production of concrete elements. On the one hand, research groups have tried to address solutions to some of the problems identified in the practice. On the other hand, they have tried to suggest new avenues that eventually can inspire new developments in practice. The Table 2 resumes the current tendencies in the realm of Research, which are then described and analysed.

Indirect intervention / Rigid Formwork / Subtraction. The fabrication of formwork noticeably continues to be a core issue in research, as it is reflected by most of the examples considered. However, there is an interest in exploring different strategies for its production with the aid of digital fabrication. To surpass the limitations of using standard EPS milled formwork, the TailorCrete project (Gramazio and Kohler 2011) [1] recently developed a wax-based formwork for complex geometries with the aid of robotic pin actuators (Figure 1). This strategy showed comparable efficiency to EPS systems but performed better in terms of the economy and ecology of the process, and of the surface finishing qualities of the fabricated pieces. At the same time, a greater level of geometrical freedom and texture expressions were made possible with EPS formwork by the adoption of 6 and 7-axis robotic arms instead of the standard 3-axis CNC routers commonly used for milling [4].



Figure 1
TailorCrete Project - Wax Formwork

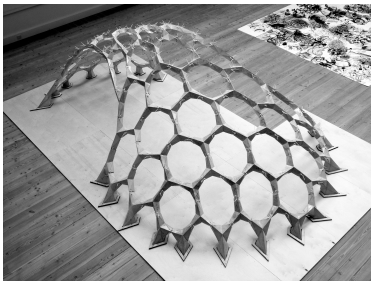


Figure 2
Pre:Vault Pavilion

Despite the traditional relation of concrete with continuous surfaces, the integration of digital fabrication technologies in the production of rigid formwork has been studied for the prefabrication of customized discrete components as illustrated by the

Figure 3
Robotic Slipform research prototype

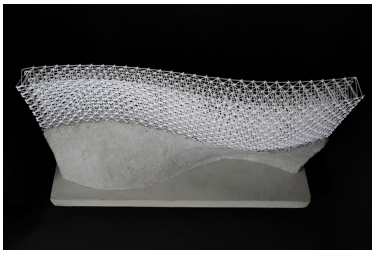
Pre:Vault research pavilion (Figure 2) (Larsen et al. 2012). In this case, laser cutting enabled the mass-customized production of digitally scripted sets of unrolled geometric surfaces that were subsequently folded into moulds for unique building components. This digital process points towards the emerging design possibilities for building complex and highly customized structural components in concrete. A similar approach was featured in the research project "Fisac Variations" for the reinterpretation of Miguel Fisac's bones system, using a robotic hotwire to produce EPS moulds for customized concrete elements (Raspall 2013).

Indirect intervention / Flexible Formwork / Subtractive. Non-rigid and non-static formwork systems have been less used in the history of concrete production; However, they are also starting to integrate digital fabrication technologies in their specific processes. Although various researchers are currently exploring the tectonic, formal and textural potential of flexible textile formwork, built prototypes and literature suggest the use of craft-based approaches for building components such as columns, beams and walls (West 2009) [2] (Manelius 2012). Digitally driven processes, such as the case of the Fatty Shell exercise (Mcgee and Pigram 2012) [3] show the relevance of integrating CNC technologies to cut unfolded complex patterns in fabric formwork solutions.

Indirect intervention / Dynamic Formwork / Additive. Dynamic formwork systems consist in those strategies that consider the displacement in space (e.g. translation) of rigid moulds to produce forms. Approaches that fall in this topic join some of the benefits of rigid formwork (e.g. the reduced difficulty of achieving smooth surfaces) with a higher degree of formal freedom through spatial movement. In the case of the Robotic SlipForm (Figure 3) process developed at the ETH in Zurich, the integration of a multi-axis robotic arm to control the vertical and rotational movement of the formwork in space, calibrating the deposition speed of the wet concrete, greatly increases the formal capabilities of an otherwise geometrically limited strategy. (Kristensen 2013)



Figure 4
MeshMould research prototype



Indirect intervention / reinforcement / formative and additive. To overcome the complex and manual labour process of creating steel reinforcement cages, the "Tailorcrete" research project has explored the automation of this process through the formative process of robotic bending[4].



Figure 5
Contour Crafting wall prototype



Figure 6
Free Form Construction panel prototype

Establishing some similarities to the ferroconcrete production system used extensively by Nervi, the problem of reinforcement and, simultaneously, of the formwork production is being addressed in the on-going research by Fabio Gramazio & Matthias Kohler "Mesh-mould" (Figure 4). This work investigates the use of a robot to 3D print the 3D mesh component that serves as reinforcement and guides the creation of the concrete element. With this fabrication system, the design of the 3D mesh can be customized to address variation, for instance, in size, geometry or density. (Hack 2013)

Direct intervention / Additive fabrication. A more recent trend in the field consists in using additive fabrication processes to directly produce concrete elements. 3D printing technologies, in which materials are sequentially solidified layer by layer to produce customized objects, have been translated to the construction scale and used concrete as a base material for printing building components. The use of these processes introduces a higher degree of geometric freedom in the production while avoiding the need of formwork. Currently, two of the most consolidated examples of this strategy are Contour Crafting (Figure 5) (Koshnevis 2006) and "Freeform Construction" (Figure 6) (Lim et al. 2012), which already proved the feasibility of 3D printing functional concrete elements. In the first case, mainly wall segments were produced, optimized to speed-up the production and obtain smooth surface finishes. In the second case, the built prototypes proposed a larger emphasis on formal freedom. (Lim et al. 2012)

Facing the inherent promises, this technological trend still reveals some limitations. For instance, attaining formal freedom is mostly dependent on two key issues: printing resolution, which is mainly defined by the height of concrete layers and the diameter of the printing head, and the need for secondary structures to support the hanging parts. These constraints contribute to design lower curvatures in height, when compared with concrete elements made with milled formwork, and feature additional difficulties in creating voids in planes orthogonal to the base printing plane. Also, in terms of surface finishing, both technologies still leave distinctive marks in produced elements, which are not fully desired. This feature must be improved towards its implementation in practice.

An alternative approach using the same tech-

nology was presented by Neri Oxman (2011), entitled "Variable-Density Graded Fabrication of Concrete". Instead of the design geometry of a product, this research is focused instead in its material composition. Using additive fabrication in a robotic printing platform, it looks for controlling the material properties and cellular structure of concrete, following the inspiration from the gradient structures presented in natural systems. This approach enables decoupling form from expected structural behaviour in concrete structural elements, as well as allowing the modulation of some properties (e.g. colour, texture) in concrete surfaces.

Direct intervention / Subtractive fabrication. All previous applications of digital fabrication technologies occur in different moments prior to or during the casting of concrete. However, a few were found that directly transform the produced concrete element in other forms or textures.

For instance, and considering the use of a concrete composite, the [c]shape Pavillion built at the Architecture Association in 2008 employed over 850 glassfibre-reinforced concrete panels, which were cut with CNC technology. Also, there are some experiments of cutting prefabricated concrete blocks using a diamond wire attached to a robotic arm in the construction of self-supporting assemblies (McGee et al. 2012). Both situations point out to the possibility of CNC post-processing operations directly over the concrete elements for the materialization of geometrically complex assemblies.

CONCLUSION

Recognizing the current dissemination of using digital fabrication technologies in architecture this paper investigate the state of the art of their application in the production of building elements in concrete. From the presented survey, its seems that the use of these processes has served more to fulfil the desire of materialising expressive forms rather than that of achieving customized surface effects.

In pursuing an increasing level of formal complexity in the built works, this study reveals the natural predominance of recurring to the use of subtractive processes to produce customized formwork. This general tendency in practice, raises an important concern with sustainability, which makes the research efforts on additive processes a promising technological alternative.

Although the surveyed works in practice and research are concerned with surface smoothness, few examples have been found trying to exhibit new texture effects from digital fabrication means. In most cases, the surface texture of exposed concrete is mainly regarded as technical concern to be addressed rather than as a topic of design exploration. Nonetheless, the existing technologies and examples shown, in direct and indirect subtractive fabrication, suggest the possibility for the expansion of textural effects. One possible path lies in acknowledging the inherent properties of specific technologies and integrating them into the design stage, as was found in some of the historical examples mentioned in the second chapter of this paper.

Finally, although it has been a recurrent research topic in contemporary architecture, the exploration of the material composition is still underdeveloped in relation with other digital fabrication trends. The concept of its controlled variability is therefore an exciting new theme that can yield interesting aesthetic, formal and structural results.

The wide set of technologies mentioned throughout the analysis establishes different relations with the materiality of concrete, depending on the specific role each plays. Whether working directly on concrete elements or, indirectly, in the formwork production, it is interesting to notice how technology options can be intrinsically linked with the design languages. The works presented in this paper thus show the exploration of a variety of geometries such as free-forms, ruled surfaces, single-curved shapes or extruded forms.

Because no identifiable process can be used to achieve all desirable outcomes in construction, it is foreseeable that several research works will make their way into the architectural practice. It is our un-

derstanding that the these particular languages as well as other material imprints emerging from specific technological processes can become relevant sources for new effects and material expressions in concrete and should be further developed in the future.

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ELEMENTOS COMPÓSITOS EM BETÃO COM GEOMETRIA COMPLEXA POR PROCESSOS DE FABRICO AUTOMATIZADO



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SUMÁRIO

A integração emergente de tecnologias de fabricação automatizada na industria da construção revela, no contexto atual, grandes potencialidades para a revisão dos processos construtivos tradicionais em betão, procurando suplantar de forma sustentada a normalização e repetição características da construção corrente em betão.

Fazendo parte de uma investigação alargada sobre processos de fabricação automatizada em betão, este artigo considera o estado de integração das tecnologias de fabrico aditivas e subtrativas em betão em obras contemporâneas, para focar dois problemas fundamentais: a produção de elementos em betão com **geometrias complexas** e a criação de **variabilidade material** funcional em elementos de betão.

Para o efeito é apresentada uma experiência prática que, convergindo estes dois interesses, investiga a viabilidade da criação de elementos com dupla curvatura e betonagens estratificadas com moldes em EPS, por processos de fabricação digital subtrativa.

Com o presente trabalho pretende-se demonstrar as possibilidades emergentes ao nível da produção de variabilidade formal e material em betão e apontar o interesse estético e funcional resultante, antevendo as possibilidades futuras para a sua aplicação na construção.

Palavras-chave: Betão, CAM, Fabrico Digital, Variabilidade.

1. DESAFIOS DA ARQUITETURA CONTEMPORÂNEA EM BETÃO: VARIAÇÃO FORMAL E MATERIAL

A inovação tecnológica tem sido um importante impulso para a arquitetura, sucessivamente dotando arquitetos e engenheiros de novas soluções para problemas existentes. Através deste processo evolutivo, os projetistas têm sido capaz de se libertar de constrangimentos construtivos para explorar novas possibilidades até então impossíveis ou impraticáveis de traduzir para a realidade.

Nas últimas décadas, a transição de tecnologias avançadas de desenho e fabricação digital (CAD/CAM) para a arquitetura tem estimulado o desenvolvimento de soluções arquitectónicas de grande complexidade, propondo a necessidade de um nível de customização fora das possibilidades da indústria tradicional.

Colocando neste âmbito a natureza material do betão, salientam-se duas características fundamentais neste material que sugerem importantes desafios e oportunidades para o seu desenvolvimento futuro: a sua plasticidade formal e a sua composição sintética como agregado de vários materiais.

Desta forma, no contexto atual, em que o desenvolvimento das tecnologias CAD/CAM proporcionam um novo nível de personalização consideramos que as duas características referidas representam os dois principais desafios para a arquitetura contemporânea em betão: a *variação formal* e a *variação material.*

1.1 Variação formal

A plasticidade do betão tem sido um tema fértil de exploração ao longo da sua história como material de construção, quer ao nível da definição de novas linguagens arquitectónicas, quer no sentido da exploração de formas construtivas complexas. Tal aspecto foi especialmente relevante durante a primeira metade do século XX, na construção de cascas de betão armado com geometrias regradas por arquitetos e engenheiros como Pier Luigi Nervi (1891-1979), Eduardo Torroja (1899-1961), e Felix Candela (1910-1997). Durante este período, a existência de uma mão-de-obra relativamente barata permitiu a construção dos sistemas de cofragem necessários para materializar este tipo de formas complexas em betão [1]. No entanto, nos anos seguintes, os crescentes custos da mão-de-obra, aliados à redução de custos possibilitada pela normalização de elementos de cofragem reduziu substancialmente a solicitação destas geometrias e provocou uma adoção generalizada de formas prismáticas na arquitetura em betão.

Atualmente, em parte pelo avanço das tecnologias de representação e modelação tridimensional, assiste-se na arquitetura ao ressurgimento de formas de elevada complexidade e irregularidade geométrica que sugerem novamente a utilização de betão na sua materialização. Esta tendência vai agora além das geometrias regradas e regulares, propondo superfícies matematicamente complexas e de difícil racionalização.

No panorama nacional, são ainda comuns, processos manuais para na criação de formas complexas em betão, nomeadamente a utilização de moldes em fibra de vidro ou polímeros líquidos, a partir de positivos com a forma pretendida. Estes processos pressupõem custos de mão de obra elevados e uma baixa capacidade de repetição, factores que impossibilitam a sua solicitação em cenários de personalização em grande escala, limitando consideravelmente o seu uso.

1.2 Variação material

Paralelamente, assiste-se hoje também a uma ávida exploração material sobre o betão, tendo em conta alterações aos seus principais elementos constituintes (matriz, agregados, reforço ou aditivos) para desenvolver novas capacidades de desempenho em vários níveis funcionais e estéticos. Desta forma, encontram-se hoje diversos tipos de betões com alterações ao seu desempenho tradicional em diferentes propriedades, especificamente pensadas no sentido de colmatar necessidades estruturais ou obter novas expressões estéticas. Desde as alterações mais comuns de resistência ou elasticidade a propriedades mais sofisticadas, como a sensibilidade à luz ou à humidade.

Independentemente das suas propriedades, este material é sistematicamente utilizado na construção de uma forma homogénea, ou seja, não existe variação das suas propriedades ao longo de um elemento construtivo. Este facto corresponde diretamente à cultura prevalente na engenharia e arquitetura, caracterizada pela discretização de funções entre diferentes elementos (ex: estrutura, isolamento e revestimento) que começa agora a ser colocada em causa.

Em oposição a esta lógica de materiais com composições uniformes e funções singulares, encontram-se, a partir da última década do século XX, materiais com propriedades distribuídas de forma não uniforme, intitulados *Funtionally Graded Materials* (FGM). Estes materiais, embora desenvolvidos principalmente pela indústria aeronáutica [2], têm proporcionado nos últimos anos algumas abordagens ao tema da variabilidade material no âmbito da arquitetura e engenharia, principalmente através de conceitos de bio-mimetismo para optimização de estruturas. [3]

Com efeito, a natureza compósita do betão, denota uma fácil alteração das suas propriedades pela composição da sua mistura, colocando-o numa posição privilegiada para ser utilizado neste âmbito. Caso se desenvolva a capacidade de criar elementos de betão com propriedades materiais distribuídas heterogeneamente, poderão desenvolver-se novos paradigmas para a sua utilização na arquitetura e engenharia, possibilitando a introdução e modelação de várias funções em elementos únicos de betão.

Esta investigação representa uma primeira abordagem experimental à integração destes dois temas, explorando a possibilidade de utilizar tecnologias de desenho e manufaturação digital (CAD/CAM) para fabricar elementos em betão de elevada complexidade formal, incorporando simultaneamente diferentes propriedades materiais.

2. PROCESSOS CAD/CAM NA VARIAÇÃO FORMAL EM BETÃO

Como primeira contextualização deste trabalho, é relevante expor sumariamente estado da arte das estratégias existentes para a produção de elementos com geometrias complexas em betão, recorrendo a tecnologias CAD/CAM.

Nas últimas décadas, o rápido desenvolvimento destas tecnologias levou ao desenvolvimento de várias soluções diferenciadas para este problema [4], correspondendo essencialmente a dois grupos principais, de acordo com os processos empregues.

2.1 Processos subtrativos para a produção de moldes.

A fabricação subtrativa pressupõe, a partir da informação contida num modelo tridimensional, a remoção sucessiva e controlada de camadas de material de um bloco inicial, por uma máquina de controlo numérico computorizado (CNC). No âmbito da construção em betão, este processo é maioritariamente utilizado na produção customizada de moldes ou elementos de cofragem em madeira ou espumas sintéticas, aproveitando a liberdade geométrica e precisão inerentes ao processo.

Um exemplo recente pode ser encontrado na obra *Spencer Dock Bridge*, em Dublin, na Irlanda, construída em 2009. Neste caso, a variação formal proposta foi obtida pela utilização de um sistema de cofragem misto, com uma estrutura de madeira, preenchida por moldes em Poliestireno Expandido (EPS) de alta densidade. A dupla curvatura destes elementos realizou-se pela maquinação de uma fresadora de 5 eixos, sendo posteriormente revestidos com várias camadas de resina epoxi garantindo a qualidade do acabamento nas superfícies de betão [5], [6].

Por enquanto, o processo de fabricação subtrativa de moldes é a estratégia mais eficiente para a produção de elementos com geometrias complexas em betão, já adoptada na prática da construção em várias edificações. No entanto, mantém-se ainda como uma solução tecnológica de exceção.

2.2 Processos aditivos para a produção de elementos de betão.

A fabricação aditiva é um processo de criação de objetos a partir de informação de um modelo digital, por sucessiva deposição de camadas de matéria. Este processo, desenvolvido inicialmente para prototipagem em impressoras 3D, foi nos últimos anos transportado para a indústria da construção, substituindo-se os plásticos normalmente utilizados por vários tipos de argamassas de cimento desenvolvidas para o efeito.

Um exemplo relevante deste processo foi desenvolvido na Universidade de Loughborough por Richard Buswell, denominado por *Freeform Construction* [7]. Ainda em fase de desenvolvimento, esta tecnologia propõe a fabricação automatizada em grande escala (2mx2mx2m) de elementos maciços em betão pela extrusão vertical de uma argamassa em camadas sucessivas, controlada por um sistema CNC com 3 eixos.

A ausência de elementos de cofragem e a precisão do processo possibilitam a construção de elementos com uma grande complexidade geométrica, assim como uma total customização de cada peça produzida sem custos adicionais. Não obstante, encontram-se ainda algumas lacunas, nomeadamente ao nível das geometrias possíveis sendo por exemplo difícil a produção de formas com zonas em balanço sem suportes adicionais.

As estratégias aqui apresentadas para a produção customizada de geometrias complexas revelam também pistas para a introdução de variabilidade material em elementos de betão. A facilidade de produção de moldes complexos, assim como a possibilidade de impressão 3D em betão sugerem dois caminhos para obter níveis diferentes de variação material que irão ser introduzidos na secção seguinte.

3. VARIABILIDADE MATERIAL EM BETÃO

De acordo com uma análise da bibliografia e exemplos existentes, propomos a divisão das abordagens a este tema em dois tipos diferenciados de acordo com a sua natureza microscópica ou macroscópica: i. variabilidade contínua ou ii. estratificada.

3.1 Variabilidade contínua

Variabilidade material contínua, é a característica principal dos FGM, definidos por Wiscombe [2] como materiais cuja composição varia gradualmente ao longo de uma superfície, resultando em modificações correspondentes nas suas capacidades estruturais e propriedades visuais.

Neri Oxman [3] adaptou esta estratégia à produção de elementos de betão, através de um processo de impressão 3D intitulando-o de *Variable Density Concrete*. Neste caso, a variabilidade é introduzida ao nível da densidade da mistura, por adição de uma espuma de alumínio, propondo a optimização da utilização do material de acordo com cargas locais específicas.

3.2 Variabilidade estratificada

O conceito de variabilidade material estratificada parte do processo tradicional de cofragem de betão, potenciado pelas tecnologias de CAD/CAM na produção de moldes personalizados. A estratificação é uma solução macroscópica para obtenção de variabilidade material, pressupondo a diferenciação de propriedades num elemento de betão de uma forma localizada com limites definidos por camadas.

Nesta estratégia, diferentes zonas materiais podem corresponder a diferentes propriedades, modeladas de acordo com as necessidades específicas, variando por exemplo entre zonas interiores e exteriores (transversalmente) ou na extensão de uma superfície, vertical ou horizontalmente.

Aplicados à construção em betão, estes processos, podem resultar em profundas alterações

na forma como desenhamos e construímos, com efeitos tanto ao nível funcional como estético. Elementos de variabilidade estratificada ou contínua podem proporcionar a um nível funcional, por exemplo, diferentes graus locais de isolamento térmico ou acústico, assim como introduzir zonas de diferente rigidez ou densidade. A um nível estético, será possível explorar por exemplo texturas ou cores diferenciadas em fachadas tradicionalmente homogéneas.

4. PROTÓTIPOS EXPERIMENTAIS

Painéis com variação estratificada

Tendo em conta os processos identificados na secção 2 e os conceitos analisados na secção 3, propôs-se uma experiência de exploração de processos de fabrico subtrativo na materialização de elementos estratificados com geometrias complexas. Nas subsecções seguintes irão ser apresentadas as especificações relevantes a intenções e desenho, metodologia e resultados.

Como primeira abordagem aos conceitos aqui expostos, seguiu-se o intuito de integrar nesta investigação o desenho e a sua materialização, de modo a perceber as implicações práticas da utilização de ferramentas avançadas de desenho e fabricação (CAD-CAM). Entendeu-se portanto necessária a realização de um conjunto de protótipos que englobassem desde cedo uma componente funcional concreta e um desenho específico, para além de provetes de teste. Deste modo, propôs-se a concepção e produção de dois painéis com dupla curvatura com o objectivo de:

i. Painel A - testar a complexidade geométrica possível com as técnicas propostas
ii. Painel B – considerando a complexidade formal de A, testar a possibilidade de introduzir variabilidade material em elementos de betão, de forma estratificada.

4.1 Considerações formais

Tendo em conta as tecnologias descritas na secção 2, selecionou-se para investigação, o processo subtrativo de fresagem CNC para a produção dos moldes necessários à betonagem das peças propostas. Sendo que cada processo de CAM assume um conjunto determinado de constrangimentos geométricos, é importante ilustrar estes limites no âmbito da produção de elementos arquitectónicos.

Neste sentido, os painéis foram desenhados no software de modelação 3D Rhinoceros, com um conjunto de ferramentas que permitiram testar a exequibilidade de formas complexas a vários níveis. Com dimensões gerais de 40x80cm, estes elementos são descritos por duas superfícies NURBS de dupla curvatura, não regrada, tornando impossível a sua descrição por métodos tradicionais de cofragem de madeira ou outra subdivisão sem recorrer a métodos de racionalização geométrica. (figura 1 - esquerda)

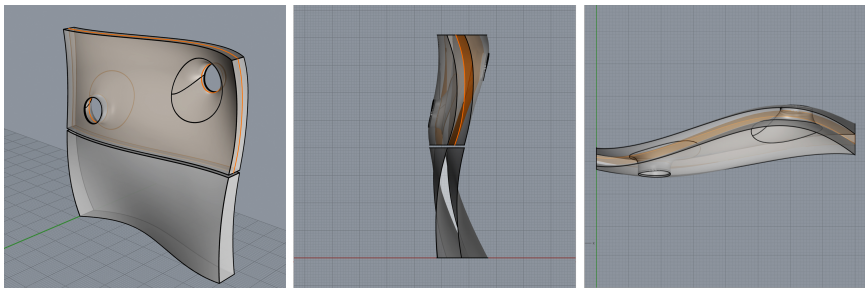


Figura 1. Modelo digital dos painéis A (baixo) e B (cima)

Além do problema de materialização de superfícies de dupla curvatura, incluiu-se uma variação da espessura geral dos painéis nos três eixos (entre 4,5cm e 8,5cm), não havendo paralelismo nas suas faces maiores.

No painel B introduziu-se uma separação ao longo da sua espessura, não paralela a nenhuma das faces, dividindo-o em duas camadas e criando a estratificação proposta. Foram ainda criados dois vazios - perfurações - circulares, desenhados como variações tangentes à superfície de cada face, resultando em duas formas afuniladas com direções opostas, como pode ser observado na *figura 1* (direita).

Finalmente, procurando testar a precisão da tecnologia de fabrico dos moldes, os painéis foram desenhados com uma geometria contínua entre eles, a partir de uma secção horizontal das superfícies originais.

4.2 Considerações materiais

4.2.1 Moldes

Tendo em conta as dimensões dos painéis, assim como a sua complexidade geométrica, os moldes foram fabricados a partir de blocos maciços de EPS com dimensões iniciais de 50x50x100cm. Dada a pressão prevista do betão sobre os moldes durante o processo de betonagem assim como as características materiais do betão e o processo de betonagem escolhido (vertical), ao contrário de outras experiências analisadas na literatura [8], optou-se por se utilizar uma estrutura de cofragem exterior, envolvendo o molde em EPS no seu interior. Desta forma foi possível garantir a ausência de deformações e a estanquidade necessária ao processo de betonagem.

Para se conseguir a geometria proposta para as peças, assim como a variação material do segundo painel, criaram-se cinco moldes diferenciados: dois para o primeiro painel e três para o segundo painel estratificado com perfurações.

Com base nos modelos digitais produzido, maquinaram-se os blocos de EPS com uma máquina de comando numérico computorizado (CNC) de 3 eixos, com uma ferramenta final

de acabamento de 5mm de diâmetro, garantindo uma textura das superfícies consideravelmente lisa (*figura 2*), com apenas algumas zonas onde são perceptíveis as marcas do processo de maquinação.

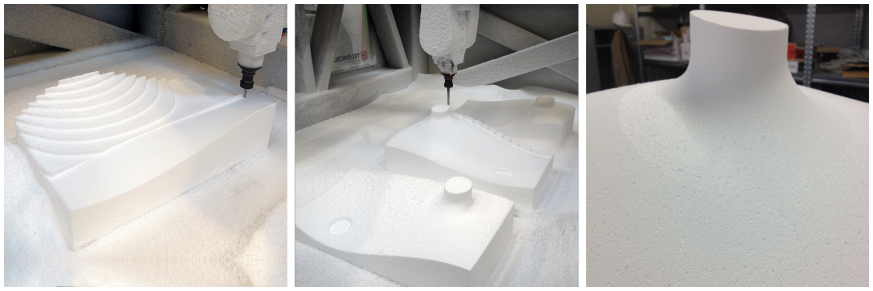


Figura 2. Processo de maquinação de moldes em EPS

4.2.2 Mistura

Na definição de uma mistura de betão para a realização dos dois painéis propostos, duas problemáticas foram tidas em conta em simultâneo, maioritariamente ligadas à espessura e geometria variável das peças. Em primeiro lugar, surge o problema da ausência de paralelismo entre as superfícies opostas dos painéis. Este facto demonstrou impraticável a realização de uma betonagem horizontal aberta, optando-se por uma betonagem vertical com um molde fechado. Em segundo lugar, a existência de elementos positivos no interior do molde, gerando zonas de difícil acesso.

Desta forma tornou-se imprescindível usar uma mistura de betão auto-compactável com agregados de pequenas dimensões e uma viscosidade adequada. Desta forma tornou-se possível o preenchimento completo do molde sem a necessidade de vibração, o que se demonstraria difícil pela dupla curvatura das peças em causa. Pelas mesmas razões, evitou-se realizar qualquer armadura metálica, recorrendo-se a um reforço com fibras de polipropileno.

Para esta experiência inicial, propôs-se uma variação material com um propósito meramente estético, realizada por alteração da tonalidade do betão, recorrendo à adição de cinzas volantes em substituição do fíler calcário numa das misturas.

4.3 Processo

Em ambos os painéis, após a maquinação dos moldes de EPS, estes foram fixados à estrutura de suporte e cobertos com uma camada de óleo descofrante, deixando o topo aberto para a betonagem vertical.

No caso do painel A, sem estratificação, seguiu-se uma betonagem simples, com um tempo de cura de 72 horas, e descofragem posterior. No caso do painel B, com estratificação, seguiu-se um processo iterativo por etapas. Após uma primeira betonagem seguiu-se uma cura de 24 horas, a descofragem de uma das secções dos moldes, a colocação e encaixe da nova secção, prosseguindo-se com uma nova betonagem com a segunda mistura auto-compactável, como ilustrado na *figura 3.* Neste painel foi crítico controlar os tempos de secagem para garantir uma boa adesão entre as camadas.

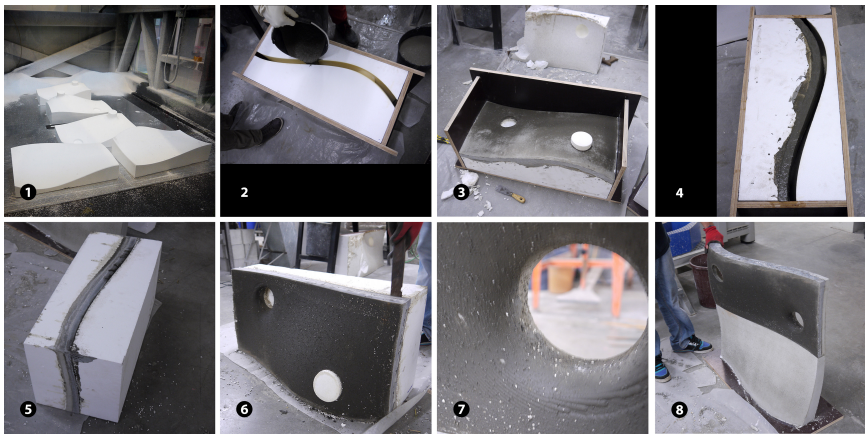


Figura 3. 1 - Moldes, 2 - Primeira betonagem, 3 - Descofragem, 4 - Montagem do segundo molde, 5 - Segunda cura, 6 - Descofragem, 7 - Detalhe da superfície, 8 - Painéis montados

5. DISCUSSÃO

As tecnologias de fabricação digital por subtração, utilizadas nas experiências mencionadas neste artigo, compreendem algumas oportunidades e limitações que foram revisitadas nesta experiência prática e recolocadas no contexto da estratificação material.

No âmbito da fabricação, foi possível perceber de forma muito clara a rapidez e precisão características a este processo, e a sua aplicabilidade à realização de elementos personalizados, executando com semelhante facilidade peças com um elevado grau de customização. Num processo relativamente rápido, foi permitindo incluir numa única peça de cofragem todos os encaixes e elementos necessários para a criação da geometria e vazios projetados.

Embora a liberdade geométrica deste processo seja elevada, os limites geométricos do processo aqui utilizado, nomeadamente, os 3 eixos de maquinação utilizados, revelaram também o limite geométrico possível de materializar por este processo. Nomeadamente a direção em Z imposta pela ferramenta impediu a existência de zonas de sobreposição ou

escavação intermédia, obrigado, por exemplo, ao desenho dos elementos positivos em superfícies opostas dos moldes.

Embora as propriedades materiais da mistura auto-compactável utilizada, tenham possibilitado em grande parte a realização da geometria proposta, a sua utilização em moldes de EPS maquinado revelou algumas limitações do uso deste material enquanto molde, sem a utilização de outro sistema de acabamento. Neste sentido, a textura final das superfícies revelou alguma rugosidade proveniente da porosidade do molde.

Não obstante, foi também possível perceber na textura dos painéis, as marcas do processo de maquinação, transferidas pelo molde. Este aspecto, embora não explorado, revelou-se num elemento plasticamente interessante e possível de ser desenvolvido pelo controlo do processo de maquinação, na fase de desenho e preparação dos moldes.

Finalmente, esta experiência levantou também uma importante questão ao nível da sustentabilidade. A utilização de processos de fabricação subtrativa, em qualquer que seja o material de base, implicam a destruição de uma grande quantidade de material. Da fresagem dos blocos de EPS resultam grandes quantidades de micro-grânulos de EPS que são dificilmente recicláveis e os moldes em si, raramente são reutilizáveis, sendo danificados no processo de descofragem.

6. CONCLUSÃO

Este trabalho procurou investigar um método de produção (em curso) de elementos em betão de geometria complexa e composição variável que possam corresponder a alguns dos interesses e desafios da arquitetura contemporânea. Para tal, propôs-se uma metodologia de realização de elementos estratificados com uma geometria complexa por processos de fabricação digital subtrativa, implicando betonagens iterativas para atingir um elemento final compósito, explorando os temas da variabilidade formal e material no betão.

A investigação envolveu a criação de dois protótipos sobre a forma de painéis com geometria complexa e, independentemente das limitações referidas, esta experiência demonstrou a possibilidade e viabilidade de introduzir uma componente de variabilidade material em elementos pré-fabricados em betão, independentemente do grau de complexidade da sua forma.

Esta experiência representou uma abordagem inicial ao tema da variabilidade por estratificação, abrindo novas perspectivas sobre as possibilidades de modelação das propriedades formais, estéticas e funcionais deste material a um nível macroscópico, através da sua aplicação de uma forma não homogénea.

Neste sentido, tendo em conta os resultados obtidos na experimentação prática e os conceitos propostos anteriormente, prevê-se no futuro a continuidade desta linha experimental, em duas fronteiras particulares: a exploração de outros materiais e processos para a fabricação de moldes, procurando optimizar a sua produção de uma forma rápida e

sustentável, assim como testar a possibilidade de criar elementos compósitos com variações de propriedades funcionais em betão, como por exemplo, a sua capacidade de isolamento térmico ou acústico.

AGRADECIMENTOS

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Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting.

Form, Texture and Composition

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In recent years, digital fabrication technologies have enabled renewed explorations into traditional materials, with innovative results. This paper focuses on concrete and on the potentials of a specific technology: robotic hot-wire cutting for the production of expanded polystyrene (EPS) formwork. Academia and industry have explored this process recently but the number of works built with this technology is reduced and the general concrete prefabrication industry has been slow to adopt it. In this context, this paper analyzes the use of EPS in the production of concrete formwork by reviewing its application in contemporary examples. In order to develop a clear assessment of the possibilities of expanding prefabrication in concrete using robotic hot-wire cutting, this paper also documents a set of practical experiments developed in the laboratory, addressing three material challenges: form; texture and composition. This research involved the design, formwork production and casting of concrete elements to explore the limits and characterize the process of robotic hot-wire fabrication in the context of concrete prefabrication. By recognizing the different approaches present in contemporary examples and in the explored practical experiments, we point out the advantages and limitations of using hot-wire cutting, and develop the reasons behind its limited application in practice.

Keywords: *Digital Fabrication, Concrete, Hot-wire cutting , Prefabrication, Formwork*

INTRODUCTION

A case for concrete digital prefabrication

Concrete is largely regarded as the most consumed, man-made material today. Its availability, mechanical properties and ability to take on any shape desired has enabled its use for almost any kind of structure. For this reason, in 2013, 4 billion tons of cement were produced for an estimated consumption of over 33 billion tons of concrete, worldwide [1].

Concrete construction technologies are traditionally based on the repetitive, undifferentiated and labor-intensive fabrication of formwork elements, which correspond to a large part of the construction costs related to this material (Johnston 2008). This not only contributes to the general waste production and natural resource consumption of the concrete industry, but has also been a relevant limiting factor to the realization of complex shaped elements in concrete architecture.

The development of pre-fabrication in concrete, in the early 20th century, addressed the problem of formwork costs by applying the industrial principle of standardization to the production of concrete elements. By placing the fabrication in a controlled environment where variation is reduced and reusability is assured, it became possible to reduce costs and production times with the effect of further limiting formal possibilities. During this time, the austere aesthetic and rational logic of the modern movement found traction with the formal restraints and efficiency of prefabrication and by extension, standardized formwork. For this reason, although the plastic character of concrete was one of its main features, this was not apparent in most of the architectural practice for a large part of the last century.

In this background, the contemporary emergence of digital design and fabrication processes and its introduction in concrete construction represents one of the biggest prospects for renovation of our built environment. These processes present a particular opportunity to reconsider the sustainability of our construction technologies and their impact on the development of architectural aesthetics.

While there have been several successful results of the use of digital fabrication technologies for the production of cast in-situ concrete structures, the concept of mass customization that characterizes the emerging digital condition, suggests the prefabrication in concrete can be an exciting alternative. Furthermore, mass customization, driven by digital fabrication technologies, can be a solution to the problem of repetition inherent to pre-fabrication, while simultaneously maintaining all other aspects that make this technique desirable in concrete construction.

In the foreword of the 2011 Design Modelling Symposium Proceedings, the editors name one of the introductory chapters "Digital Fabrication means prefabrication" (Gengnagel et al. 2011), citing the cost, size and fragility of the necessary equipment. In the case of concrete construction almost all examples using digital fabrication hold this statement true to some extent. The usual products of digital fabrication for concrete (moulds) are prefabricated, but more often than not, used for on site monolithic casting of concrete. As such, the interesting notion of precisely fabricated and accurately assembled components that can be equated with the use of digital fabrication technologies in architecture is lost in the translation from process, to construction and architectural expression.

It is our understanding that there is a specific relation of complementarity between the digital design and fabrication technologies, and the prefabrication of concrete that should be further explored regarding its feasibility and architectural potential.

The present paper follows a previous research into the overall impact of digital fabrication technologies in concrete (Martins P. and Sousa JP 2014) and focuses on exploring robotic hot-wire cutting as an architecturally expressive solution to the production of formwork for concrete prefabrication.

BACKGROUND

Traditional approaches for complex concrete constructions

In order to develop a clear view of the problem of materializing complex shapes in concrete, it is relevant to consider the historical exceptions to the rationalized use of concrete described earlier. Relevant examples can thus be found in the design and construction of thin shells structures, pioneered through the works of architects and engineers such as Eduardo Torroja, Felix Candela, Pier Luigi Nervi and Heinz Isler. What makes theses constructions relevant in the scope of this research is their structural dependence on complex curved geometries, the material behavior of concrete and the construction techniques developed, which allowed for the creation of very large spans with very light concrete structures.

Traditional construction techniques employed in the production of such complex surfaces in concrete commonly used wood formworks produced from straight beams, fitted with bent wood boards, either interpolating or rationalizing a general curved surface or describing the actual surface in case of ruled surfaces. After metal reinforcement was placed, a high viscosity mix of concrete was poured and troweled into place, defining the finished concrete surface. Such was the case for the Palmira Chapel, designed by Felix Candela, and built in 1959, featuring a hyperbolic paraboloid shell with 4 centimeters of overall thickness (Basterra et al. 2001).

A substantial different technique was developed by Nervi, which used lightweight, prefabricated ferrocement components as lost formwork for concrete casting. The components were prefabricated on-site and assembled to define the casting surface, becoming embedded and part of the finished structure after a final layer of concrete was poured.

The method of prefabrication and assembly of components used by Nervi and defined by Iori and Poretti (2005) as "structural prefabrication" depended on the subdivision of the surface and overall structures into manageable components, which could be built simultaneously and assembled on-site. Because of time, economical and fabrication restrictions at the time, these components were limited in variability and complexity (Iori and Poretti 2005).

While both methods can be regarded as labour intensive, it is clear that in the case of the works of Nervi, lightweight prefabrication enabled a considerable reduction in material consumption, waste production and construction time, with the clear drawback of geometrical repetition, limiting the possible design space.

The traditional techniques described in the case of the Palmira chapel are still much in use today and in some cases, have been integrated with digital fabrication technologies. Examples can be found in the construction of the Mercedes Benz Museum and the Rolex Learning Center [2]. Nevertheless, the lessons of Nervi, in time and material economy, as well as in the use of lightweight prefabricated components in large, complex assemblies are still relevant today, more so, with the emergent possibilities of digital fabrication and their applicability for greater diversity of form, precision and efficiency.

EPS moulds for prefabricated and in-situ concrete in current practice.

One of the first cases for the integration of digital fabrication technologies in concrete construction can be found in the pioneering works of Frank Gehry. The Neue Zollhof building, in Dusseldorf, Germany, was built in 1999 and featured an innovative solution for the problem of formwork production for freeform concrete surfaces, through the use of CNC milled moulds for concrete casting. Although it was also used for in-situ casting, of particular interest was the development of this process for the production of large prefabricated wall segments with ruled geometry.

At the time, a significant time reduction of the milling processes was needed to achieve the economical viability necessary for construction industry. This was accomplished through the high speed, rough milling (5cm tool bit) of expanded polystyrene (EPS) blocks (Shelden 2002). The wall components

were cast off-site into open, one-sided moulds, with standard steel reinforcement. One face was cast against the mould and the other troweled into shape, causing the transference of large tool marks from the milled formwork to the exterior concrete surface.

This process resulted in an overall low quality of the surface of the concrete that was subsequently finished with other materials. However, it is possible to imagine the difficulties of using other traditional formwork systems for the construction of the desired geometry, despite of being, predominantly composed of ruled surfaces.

CNC milled EPS formwork was similarly used for the in the construction of the Spencer Dock Bridge, by Amanda Levete Architects, built in Dublin, in 2008, although in this case, the majority of the concrete was cast in-situ, creating a monolithic structure.

For the design of the formwork, the double curved surface of the underside of the bridge was subdivided into a rectangular grid, taking into consideration standard sizes of EPS blocks. The formwork material was milled with a 5-Axis router in consecutive passes with increasing resolution, resulting in a smooth finish of the surfaces as compared with the previous example.

In order to ensure a correct demoulding and an acceptable finish for the apparent concrete surfaces, further work was necessary on the formwork with the addition of multiple sprayed impermeabilization coatings and sanding. The EPS moulds were then assembled on a plywood and steel falsework, their connection joints were sealed and false rebates created with a desired geometry

At the same time, the more complex lateral elements (double curved, with non-parallel opposing faces and connection joints) were precast off-site, using EPS milled moulds with epoxy and fiberglass coatings for reusability. (Dempsey 2008).

The case of the Spencer Dock Bridge demonstrates the feasibility of building large-scale structures with this formwork system but also the difficulty in obtaining high quality finishes, without incurring in substantial labour and production time increases.

In the time span between both examples, CNC milling and EPS formwork systems have been incorporated into the construction industry through formwork specialized companies which offer it as part of integrated systems for in-situ concrete formwork (e.g. PERI)[3] and other specialized large scale CAM (computer assisted manufacturing) industries [4].

Nonetheless, milling time in the production of EPS formwork for smooth, apparent finishes is currently measured in hours for each piece of formwork, corresponding to months for full structures. Therefore, fabrication time is a large factor in the CNC milling of EPS formwork, greatly increasing costs and relegating the use of complex freeform in concrete to exceptional buildings.

It is therefore relevant to find other, more economically viable processes that can democratize the use of complex forms in concrete. We believe that although it is an inherently limited process, Robotic Hot-wire Cutting (RHWC) can bridge this gap to become not only a viable technology, but also capable of enabling future explorations into the architectural potentials of concrete.

MATERIAL EXPERIMENTS

Precast MSE Panels

In order to assess the technical and architectural potential of RHWC, we developed a set of practical experiments, addressing specific material challenges for prefabricated concrete elements.

This work builds upon previous experiments with RHWC such as the RDM Vault (Matthias Rippmann and Silvan Oesterle), the Automated Foam Dome (Thibault Schwartz), the Light-Vault (Yuan et al. 2014), or the Opticut prototype (Feringa and Søndergaard 2014) by shifting focus from design to the particular material implications of concrete cast with hot-wire cut EPS formwork.

For these experiments, three material challenges were identified, taking into consideration their relevance to concrete and RHWC and each was addressed through the production of one or more prefabricated components:

Figure 1
MSE wall construction with precast concrete panels

1. Double-curved components (form);

2. Textured components (texture);

3. Variable materiality components (composition).

The first challenge addressed the overall problem of complex curved geometries, which in the case of RHWC, are limited to ruled surfaces, with the objective of determining the geometric constraints and limits of the technology in the production of formwork for concrete.

The second is focused in revisiting past examples of textured concrete and exploring the specific architectural possibilities for textural effects emerging from the hot-wire cutting process.

The third challenge is aligned with current interests in non-homogenous materials. It addresses the concept of a variable materiality in concrete elements, by which different zones of a single element can have different material performances, either functional or aesthetic, by using different concrete mixes with sequential castings.

The exploration into three different problems allowed us to stress different aspects of the fabrication technology to ascertain its overall relevance in diverse prefabrication scenarios.

Component design and robotic simulation

The overall design concept used for the experiments was based on the geometry of precast panels for mechanically stabilized earth (MSE) (Figure 1). MSE is a technology used for the construction of retaining walls capable of sustaining heavy loads, generally used in highways or bridges. A distinctive characteristic of this construction technique is the use of prefabricated modular concrete panels as exterior facing for the system. These are commonly quadrilateral or hexagonal, with or without interlocking joints,forming continuous, planar surfaces.



As it was not the objective to devise a new panel system for MSE, we used the geometric and modular concept of these panels, without taking into consideration their specific technical function.

The geometry of the 3 panels was modeled in Rhinoceros and achieved by vertically projecting the standard panel design onto two (or three, in the case of the third panel) parallel double curved, ruled surfaces. In order to further stress the geometric constraints for the fabrication, we ensured that the edges of the panels were not parallel to the surface ruling lines, creating 4 curved edges in each panel.

The bounding box dimensions for the three fabricated panels were 308x385x385mm, 308x385x445mm, 220x555x390mm and the overall panel thickness was 40mm, defined in accordance with the available EPS blocks (1000x500x350mm) and also taking into consideration a necessary surrounding margin of 50mm to withstand the pressure of the concrete pour. The components were orientated in the stock material regarding these needs and the objective of reducing material waste.

The robotic simulation and toolpath generation for the hot wire cutting of the EPS moulds was done in the Grasshopper plugin for Rhinoceros, using the KUKAprc software, developed by the Association for

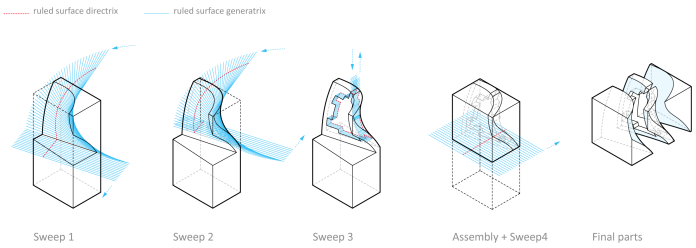


Figure 2
Robotic cutting routine (panel 1)

Robots in Architecture.

As stated before, the possible geometrical space of this technology is limited to ruled surfaces. These are determined by the movement of the hot-wire, akin to the concept of a line (generatrix or ruling) moving through space, along a curve (directrix). Using similar methods to those mentioned in previous works in RHWC, the movement of the hot-wire was programmed in the KUKAprc software by extracting two points from each ruling of the surface, plus a third outside point to respectively position the hot-wire line correctly in space and define the angle of the hot-wire bow in relation to the cut, throughout the entire sweep. The geometric design of the textured surfaces of panel 3 was obtained directly in the Grasshopper and KUKAprc definition, by alternately shifting in the y-axis, the reference points along one of the directrix curves that describe the original ruled surfaces.

Formwork design and Fabrication Process

Because of the proposed geometric complexity, we decided to use closed moulds for all of the castings. The moulds for panels 1 and 2 were designed with three separate parts: one for each front and back facing and one internal piece defining the negative space for the concrete casting. The third panel was designed with an intermediate subdivision that enabled the two castings required.

The RHWC setup at the DFL laboratory consists of a stationary Kuka KR 120 R2700 industrial robot, mounted with a 100 cm wide and 0,25mm thick hot-wire end-effector (Figure 3).

Using this setup, the cutting routines consisted of 4 cuts for panels 1 and 2 and 5 cuts for panel 3. The first cuts carved the front and back general ruled surfaces from the EPS stock block, followed by the cutting of the central void in the remaining piece. The entrance and exit trajectory for this cut became the concrete pouring channel. A final horizontal cut trimmed and separated all the parts of the mould. (Figure 2)

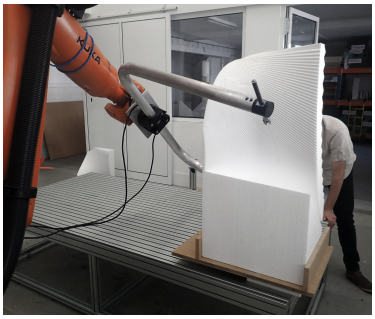


Figure 3
Robotic hot-wire fabrication process (panel 2)

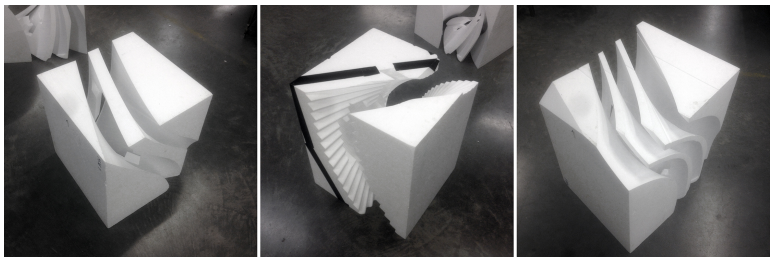


Figure 4
Fabricated EPS formwork assemblies before closing and bracing (panels 1, 2 and 3)

The fabrication process was successful, with a few practical problems, related to the hot-wire calibration. With this technology, one of the most critical parameters is the relation between cutting speed and temperature. A base line for this relation was established through trial and error after initial runs. In order to increase the accuracy of the cutting process, a relatively low overall speed (10cm/s) and temperature setting was used. Furthermore, because the wire temperature was not included in the KUKAprc definition, it was closely monitored in the final cuts, aiming at achieving a constant cut, despite of the diversity of cutting situations and their respective speeds.

Concrete Mix and Casting process

Regarding the materialization of complex geometries in concrete, one critical aspect of making these processes viable, which is not frequently mentioned, is the design of the concrete mix. The same reasons concerning geometric complexity that frequently justify the use of digital fabrication technologies for concrete production, often require custom concrete compositions to become viable. In the case of this experiment, the difficult accessibility of the moulds and the problems that would arise from using traditional metal reinforcement were taken into consideration to define a mix of self-compacting white concrete, reinforced with polypropylene fibres. For the third panel, a similar mix was used, with grey portland cement and fly ashes.

Although the material variability in this exercise was purely aesthetic, other performative changes could be explored in the same manner. For example, changes in weight, mechanical resistance, thermal or acoustical behaviour could be achieved with the introduction of different material elements in the concrete matrix.

For the casting process, the moulds were treated with a demoulding agent and a lateral bracing was applied to ensure no buckling would occur. A conscious decision was made to avoid the use of time-consuming coating applications, as was observed in earlier examples. It was our understanding that it would defeat the purpose of developing a time efficient process for formwork creation. Furthermore, it was an opportunity to study the textural quality of concrete, emerging from this process.

Panels 1 and 2 were cast and set for 60 hours, before demoulding. In the case of panel 3, we followed an iterative process for the cast of the two layers of concrete. An initial cast of the first layer, followed by a partial demoulding after 24 hours, opening of the second interior void and re bracing the mould. The casting of the second layer with the different mix of concrete followed and the final demoulding was done after 72 hours (Figure 5).

The casting phase revealed that the precision of the RHWC process as well as the fact that all parts of the moulds were cut from a single block (which would not be the case for milling) had a large impact

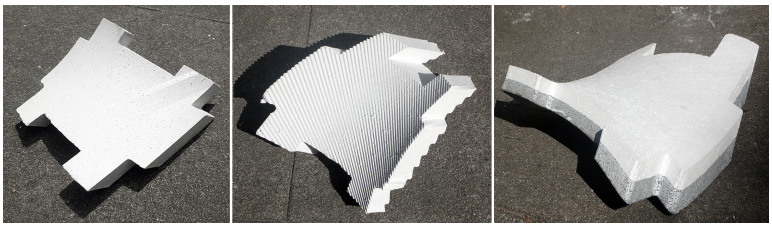


Figure 5
Finished concrete panels: Standard panel (left), textured panel (center) and variable materiality panel (right)

on the accuracy, correct fit and ease of assembly of the moulds (Figure 4).

DISCUSSION

During the execution of the described experiments, several constraints and characteristics of the process of Robotic hot-wire fabrication became apparent that should be taken into consideration for future research.

Geometrical constraints. One major geometrical constraint of this technology in surface description, especially when compared with the established freedom of other subtractive processes, is its restriction to the creation of ruled surfaces in the movement of the hot-wire through space. This unavoidable fact is the clearest limitation of RHWC. On the other hand, ruled surfaces encompass a great diversity of forms, which have a clear historical relation with architecture as discussed in the previous examples. Furthermore, the increasing tendency for freeform buildings in concrete has prompted developments into rationalization strategies for double curved surfaces, using strips of ruled surfaces, with a very high accuracy, greatly increasing the relevance for these geometries (Flory and Pottmann 2010).

Size restrictions. Taking into consideration that the size of uncut EPS blocks does not prevent the scaling of this technology to construction-scale elements, the major size constraint is clearly in the available length of the hot-wire. Nevertheless, a design problem was detected that further constrained the size of components. Because the borders of the proposed elements were not parallel with the ruling lines, the hot-wire described a diagonal movement through the blocks. This meant that the seemingly large length of the 100 centimetre wire was used in all its extension for the production of the otherwise relatively small components.

Precision. The gap left in the hot-wire cutting path that results from the melting of the EPS foam, is a function of the cutting speed and the wire temperature. For a set speed, an increase in temperature represents an increase in the cut width and for a set temperature, a decrease in cutting speed also represents an increase in cutting width. For this reason, a ruled geometry that implies a stationary point in space within the movement of the ruling line (ex. the vertex of a conic surface) results in an unwanted increased cutting gap representing a local loss of precision. These situations were mitigated by reducing the temperature below what would be overall necessary for the surface, resulting in an increased cutting time.

A similar problem was encountered when cutting surfaces at sharp angles with other cut surfaces. Because of the low thickness of the foam in these sections, it melted much easier, resulting in uneven edges, which were also compensated with low cutting temperatures and speeds.

Optimization. A usual solution to the problem of optimizing material usage when producing multiple components from large stock material, such as EPS

Figure 6
Surface quality for standard EPS formwork with demoulding agent.

blocks, is packing the desired elements using nesting techniques. In the case of the production of formwork components for concrete casting, depending on the selected casting process, we found that a balance must be struck with regard to the relevance of determining horizontal sections for concrete pouring. Although the concept of closed moulds was successful in reproducing the desired panel geometry, we concluded that the casting process would have been more efficient, with no loss of precision, if the moulds had featured one open side for the concrete pour.

Speed. Considering the conservative cutting speed used in the experiments (10cm/s), the four cuts necessary for each complete formwork took on average approximately 7 minutes. According to our early experiments in CNC milling and in line with other literature (Feringa and Søndergaard 2014), this represents a 25 fold decrease in production time directly related to the robotic fabrication process. During production, no significant practical aspects were found that reduced this difference.

Surface Quality. One of the most relevant issues regarding the acceptance of these techniques in the concrete industry is the perceived poor surface quality of the finished elements. In the case of this experiment, we found an obvious loss of smoothness in the finished surface when compared to concrete set with traditional steel and plywood formwork, that can be traced to the porosity of the untreated EPS foam. Nevertheless, most notably in the case of panels 1 and 3, we found that the resulting surface had not only an acceptable quality (Figure 6), when compared with wood board formwork, but also revealed a similarly interesting textural pattern of the hot-wire rulings that was further emphasized in the design of panel 2. We concluded that the process of RHWC, although optimized for speed of production can also yield positive results, worth of architectural exploration.



CONCLUSIONS

In light of the practical experiments conducted for this research, the advantages of the robotic hot-wire cutting process are clear. The drastic decrease in fabrication times and the material economy in comparison to CNC milling make this technology a viable solution for the production of concrete formwork. While its geometrical constraint is a significant issue, we believe that the use of ruled surfaces is still relevant today as architectural expression and as a rationalization solution for general double curvature surfaces.

From our comparison of production technologies and formwork systems, we conclude that the reasons for the slow adoption of robotic hot-wire cutting as a solution for the production of concrete architecture are two-fold: the reality of the construction industry and the interest of designers. When comparing CNC milling and RHWC, although the latter is in most cases much more geometrically constrained, we believe that this is not reason enough for its inadequacy.

One possible cause can be found in the fact that CNC milling processes have been used for a longer time in manufacturing industries before being adopted by architecture and the construction industry. As such, tools, software and the knowledge of their application is much more widespread and its integration and understanding in the architectural environment more profound.

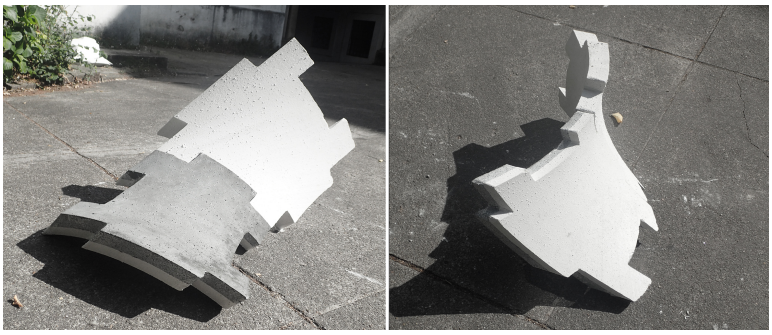


Figure 7
Prefabricated panel assembly (panels 1 and 3)

From the perspective of the designer, facing the current alternative methods of formwork production, the eventual design rationalization of a general curved surface to ruled surfaces poses a minor problem when compared to the issue of smooth surface quality, which seems to be the standard goal in the architectural practice today. When considering the general use of EPS and digital fabrication technologies for formwork production, the limiting factors are clearly the material conditions of EPS and not the technology employed. As such, other paths should be explored in the future, that assume these limitations and explore different textural qualities for concrete, while maintaining the advantages of the digital fabrication workflow.

Finally, when considering the relation between technology, materials and architectural expression, we found that in the explored case of concrete there was an interesting emergent architectural vocabulary that linked the prefabricated and assembled components to the fabrication technology. This visual and conceptual link created a specific tectonic quality (figure 8) that we intend to further explore in future experiments with prefabrication in concrete.

ACKNOWLEDGMENTS

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[4] www.nedcam.com

The Robotic production of the GRC panels in the CorkCrete Arch project

A stratified strategy for the fabrication of customized molds

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The CorkCrete Arch was an experimental prototype built in the scope of a research project concerning the use of robotic fabrication technologies for non-standard solutions in architecture. It combined 2 materials, cork and GRC into a self-supporting lightweight building system, designed to explore the integration of different robotic fabrication technologies in one constructive solution. This paper is focused in providing a detailed description and analysis of the robotic fabrication process used in the production of the GRC components. The presented solution integrated robotic milling and hot-wire cutting technologies with a stratified mold design strategy that allowed for overcoming the limitations of each and enabled a time and cost efficient production process.

Keywords: *Robotic Hot-Wire Cutting, Digital Fabrication, Glass Fiber Reinforced Concrete, Computational Design, Corkcrete*

INTRODUCTION

The CorkCrete Arch was developed as a design-based research activity concerned with using robotic fabrication technologies in the production of a novel building system. By exploring the combination of two different materials - cork and Glass-fiber Reinforced Concrete (GRC) - the goal was to merge the sustainable and insulation properties of the first with the structural efficiency of the second. The result is a lightweight and performative material system suited for customized prefabrication and easy on-site installation.

Objectives

The proposed building system was tested through the design and construction of an arch structure. Featuring double-curved and textured cork panels combined with ruled-surface GRC elements, its geometry challenged the use of robotic fabrication technologies for its production. Since it was not a single material installation, like in many actual robotic experiments, the process had to coordinate the different physical tolerances resulting from employing different materials and different fabrication processes, taking place in different locations (i.e. laboratory, factory and on-site). Working in collaboration with industrial partners, from the cork and GRC fields, this experience envisioned and tested a fabrication strat-

egy with both materials that revealed to be very productive and efficient for both areas. While an overall design and tectonic description of this project can be found in a previous text by the authors (Sousa et.al. 2016), the present paper is focused in providing a detailed description and analysis of the robotic fabrication process used in the production of the GRC components. In order to address the materialization problems, put forward by the geometry of the panels, this process explored a novel stratified mold concept, contributing to the existing state-of-the art in robotic hot-wire cutting of formwork. For its understanding and assessment, this paper describes the traditional GRC production process and recent technological innovations before illustrating the CorkCrete arch GRC components and the production strategy employed.

THE GRC IN ARCHITECTURE

GRC is a composite material developed in the late 1960s that combines the resistance and binding properties of a cement matrix, with the tension resistance properties of glass fibers to achieve thin, shell-like construction elements. The traditional fabrication processes of GRC panels can be subdivided in two: premix or sprayed. In the first case, the materials which compose the GRC are mixed in advance and cast into a mold, press molded, extruded or slip-formed. In the second, and most common scenario, the cement paste and the glass fibre are simultaneously sprayed using a two headed nozzle into a mold (Brookes and Meijs 2008). This procedure is a complex iterative manual process of depositing and compacting the mix of cement paste and fibres, and its success depends on the skill and judgment of the workers. A finishing procedure is used, depending on the necessity of different surface qualities or effects.

Architectural applications

Given that GRC components are thinner and lighter than precast concrete ones, their main use in architecture is in cladding applications. One of the first relevant works with this material can be found in the Credit Lyonnais building in London built in 1977, in which the architects developed modular elements for a window frame with curved profiles. However, since they can assume any shape depending on the mold, the use of GRC has become an increasingly popular solution in recent years to address the complex and variable challenges in contemporary architecture. Built in 2009, the Roca London Gallery designed by Zaha Hadid Architects featured an interior continuous curved space, built with 272 different self-supporting GRC sandwich panels. Despite the formal versatility of the material, the production of different molds defines the main economical constraint of the system. For instance, in the Heydar Aliyev Center in Baku, also designed by the same office, the large-scale application of GRC panels required a geometric rationalization process to define and organize the panels into planar, single and double-curved ones. Despite the exceptional economical means involved in this project this simplification process had to be considered for its construction (Bekiroglu 2010).

Technological Innovation

Due to its singular properties and its potential to match contemporary design interests, many researchers have sought opportunities for innovation in GRC production over the last 2 decades. In order to overcome geometric, manual production and economical limitations, this continuous investigation has been mainly focused in the automation of two moments: the production of molds and the spraying procedure.

Regarding the first, the use of Computer Numerically Controlled (CNC) milling processes has been adopted to fabricate complex shape molds in wood or foam parts directly from digital models. Although these subtractive processes are widely available, they are time-consuming, expensive and produce large amounts of material waste in the form of dust, which is critical for reuse purposes. To minimize these issues, other digital fabrication strategies have been developed, such as Robotic Hot-Wire Cutting (RHWC) to quickly fabricate molds in EPS for ruled surface-

based designs with minimal material waste (Feringa and Søndergaard 2012).

Regarding the automation of the spraying moment, the work in the 90's of Carlos Balaguer and José Manuel Pastor Garcia with the Spanish company Dragados y Construcciones (Balaguer et al. 1993) introduced the use of robotic spraying processes. Despite the advantages that were verified (Peñin et al. 1998), its adoption by the industry has not happened yet. In this summary it is interesting to see how the robotic arm seems to play a key role in driving the development of innovative solutions in both moments.

A STRATIFIED STRATEGY FOR ROBOTIC FABRICATION OF GRC COMPONENTS

The CorkCrete Arch was specifically designed for prefabrication. With 280cm wide and 260cm height, it is a composite system built from the assembly of 3 structural GRC elements and 18 cork panels. The geometry of the CorkCrete arch was driven by two factors: the catenary curve and the robotic fabrication technologies. On one hand, the catenary curve was used to introduce a clear structural principle in the arch. On the other, robotic fabrication technologies were used as a design driver to shape the material surfaces, which for the GRC panels signified an exploration of ruled geometries and their materialization through robotic hot-wire cutting.

The specific geometry of the 3 GRC panels posed several challenges. For each one, its interior face was designed as the intersection of two ruled surfaces producing an emergent and progressive crease in the central axis. The exterior face was delimited by two planar surfaces to connect with the flat bottom surface of the cork panels. The lateral faces of the GRC panels performs as the structural reinforcement of the thin panels, and was also designed as a continuous ruled surface, which increases in width from the base to the apex of the arch (Figure 1).

The geometric complexity of these design elements was heightened by the necessity of fabricating the corresponding negative molds for GRC spraying. The main fabrication challenge was thus the production of a large-size concave ruled surface mold with variable lateral walls. This kind of geometry requires a customized mold that can not be achieved with a single-run RHWC process, over a single raw material.

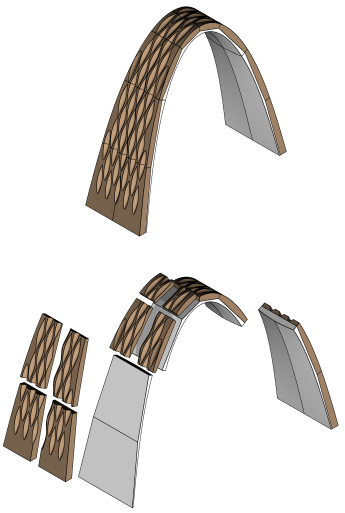
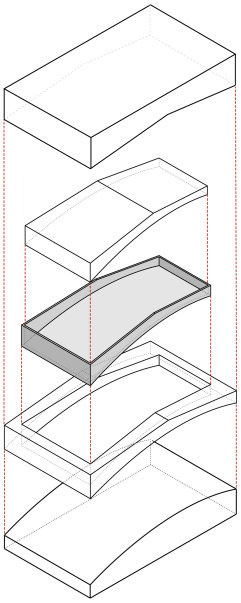


Figure 1
The Corkcrete Arch 3D model with exploded GRC and cork components.

The Stratified Concept

To overcome the challenges mentioned, a strategy for a stratified process to produce the mold was developed by taking advantage of the benefits of robotic hot-wire cutting and addressed its limitations to produce the necessary mold geometry. RHWC is generally characterized by its limitation to the production of ruled surfaces and its ability to do so with considerably low fabrication times when compared to traditional subtractive technologies (i.e. milling) (Feringa and Søndergaard 2012). Considering the

fabrication of molds in EPS, one of its main advantages is the preservation of excess material when cutting a surface. This feature enables the production of successive cuts, subdividing a stock block into several different layers. Applying this notion to formwork design results in the concept of the "stratified mold". A subdivision of a mold geometry into several layers, cut from a single EPS block in a short time span and assembled into a final mold that couldn't otherwise be produced with RHWC technology.



Following this concept, the molds for the Corkcrete Arch GRC panels were subdivided into 3 layers to be sequentially cut: the bottom surface; the contour layer, creating the lateral structural folds and the overall boundary geometry of the panels; the top surface, defining the exterior flat surface of the panels (Figure 2). To overcome size and geometric constraints (the size of the available hot-wire and the concave, intersecting ruled surfaces), each mold was divided in two halves through their central axis for fabrication, resulting in six halves for the three GRC elements.

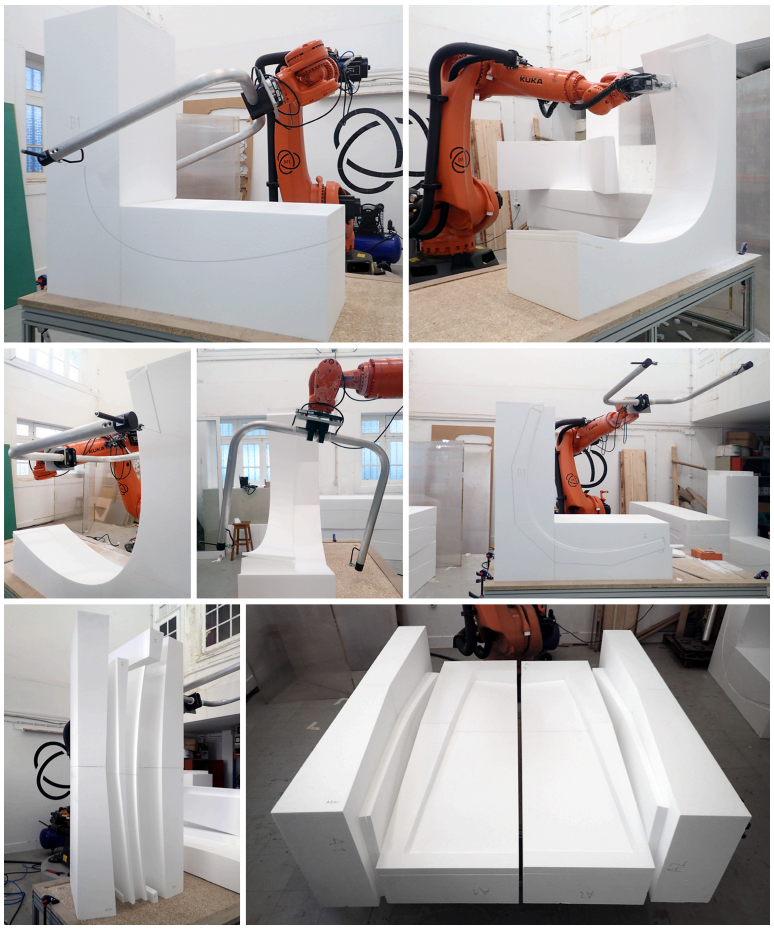
Robotic Fabrication of the Molds

The RHWC system at the DFL laboratory consists of a stationary Kuka KR 120 R2700 industrial robot, mounted with a 100 cm wide hot-wire bow, featuring a 0,25mm thick wire. Simulation and toolpath generation was done in the Grasshopper plugin for Rhinoceros, with the Kuka|prc software, developed by the Association for Robots in Architecture. Using this setup, the molds were produced from combinations of 100x50x50cm high-density EPS blocks as stock material, with the expected seams considered in the design of the arch elements. The fabrication routines were composed of four cutting operations performed sequentially: (a) hot-wire cut to define the interior surface of the arch and removal of the resulting top half; (b) milling of the ruled contour of the panel with a 20mm diameter bit, in a single pass; (c) hot-wire cut, defining the planar surfaces for the exterior face of the GRC elements; (d) hot-wire cut of the EPS core resulting from the previous operations to fit the interior of the panels (Figure 3). Independently of surface complexity, each routine was completed in approximately 10 minutes for all 4 cuts, a relatively fast process when compared to the necessary hours of CNC milling to achieve similar finishing quality.

After the fabrication process, the first and second mold layers were assembled and glued together, along with their corresponding halves. Because the GRC spraying process requires an open mold, the third layer was not necessary, being only used for stacking and transportation purposes. Nevertheless, if necessary, the process could have been further optimized to nest more molds in the remaining EPS ma-

Figure 2
The stratified concept applied to the Corkcrete Arch molds: bottom surface layer; contour layer; sprayed GRC panel; interior core; outer layer.

Figure 3
Mold production process featuring the four sections for the center GRC element: bottom curved layer, contour milling, top flat layer and interior core cutting. Completed mold pieces for the bottom arch elements, illustrating the mold subdivision.



terial. At this stage, the robotic fabrication phase proved to be a straightforward process, clearly adaptable for larger production scales, maintaining economic viability.

The GRC Production

The production of the GRC panels took place at a precast facility of the projects' industrial partner, Mota-Engil, S.A.. Minimal work was done on the mold surfaces and a simple coating of demolding oil was applied in order to minimize the overall production time and costs. Before the spraying procedures took place, a set of metal anchor elements was introduced in the molds to be embedded in the GRC matrix for transportation and as fasteners between the 3 arch elements. The spraying process used a white GRC mix to make a clear distinction between the two materials and to accentuate the geometric features of the arch. It consisted of an initial layer of GRC with an average thickness of 15mm, followed by manual compaction. After this step, the EPS cores were placed inside the mold and a finishing layer was applied. Embedding the excess EPS cores in the panels added to the structural stability of the system and created a suitable support surface for the cork elements. After curing for 24 hours, the panels were easily demolded and shipped inside the used molds.

The robotically produced molds were effortlessly used in the industrial setting of the precast facility by the workers. They proved to be suitable for regular spraying equipment and operating procedures without adaptations or special knowledge required, validating its usage in this environment. (Figure 4)

Results and Installation

As expected, the surface quality of the GRC panels was not completely polished as is the case with traditional flat steel molds. Nevertheless it had an acceptable smooth finish. This is due to the porosity of the EPS material which enables the transference of its cellular texture the finished surfaces. Also, faint marks of the hot-wire could be found on the fi-



Figure 4
GRC production process: spraying and EPS core positioning; center arch component after demolding.

nal surface which were traced back to vibrations of the wire during the cutting process. Although unintentional and generally undesired, these textural elements added an interesting aesthetic layer as fingerprints of the fabrication process. After the production of the GRC components and the corresponding cork panels, the Corkcrete Arch was manually assembled several times in different settings, without mechanical aid (Figure 5). This demonstrated the lightweight properties of the system and suggested the feasibility of expanding it for larger applications. The assembly stage also confirmed the accuracy of the robotic fabrication process. Small geometric deviations from the modeled geometry were found to be well inside construction tolerances and were absorbed in the construction joints of the arch system.

CONCLUSION

The research presented in this paper addressed the problem of producing custom molds for non-standard GRC components in a composite building system. To achieve this goal, the authors devised a stratified strategy that combined the efficiency of hot wire cutting and milling in one fabrication process.

The produced results revealed the flexibility and versatility of the use of robots in relation to traditional CNC systems, by being able to use different tools and optimize their inherent abilities. The stratified mold strategy proved to be a time, material and cost-efficient solution for the production of complex molds when compared to both traditional manual methods and contemporary milled formwork. The validation of this solution in an industrial setting promoted the interest of the precast industry in continuing the research into this topic. In this regard, further developments will seek other applications of the



Figure 5
Manual assembly process and finished arch structure. A continuous geometrical transition between ruled surfaces and the well defined central crease reflecting the precision of the robotic fabrication process.

stratified mold strategy and address 2 key issues: improving the surface quality of the GRC without incurring in a substantial increase in production time and optimizing stock material usage.

ACKNOWLEDGMENTS

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The Tectonics of Digitally Fabricated Concrete. A Case for Robotic Hot Wire Cutting

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Abstract. In the last decades, digital fabrication technologies have stimulated the materialization of complex and customized solutions in several materials. Recently, the integration of these technologies with such a variable and rich material as concrete has prompted an explosion of possible processes and outcomes for digitally fabricated concrete structures. In this context, this paper examines current digital fabrication strategies for concrete, focusing on their applications and in identifying critical issues for their adoption. From this point, through the presentation of two case studies, we propose and discuss Robotic Hot Wire Cutting as a technically and tectonically relevant digital fabrication technology for customized concrete architecture.

Keywords: Concrete · Digital fabrication · Robotic Hot Wire Cutting

1 Introduction

1.1 Form, Surface and Composition

In the last 30 years, the dissemination of digital design and fabrication technologies in architecture has inspired and enabled the production of increasingly complex and customized design and constructive solutions [1]. Concrete is a particularly relevant material in this context. Its ability to assume virtually any shape has, throughout history, enabled architects and engineers to explore its plasticity in complex free forms, hardly achievable through other materials. In turn, their construction process has been one of the main challenges of concrete architecture, presenting technological, economic and material limitations to the realization of the most complex solutions.

Yet, it was through this construction process that most of the aesthetic and tectonic value of concrete architecture was defined. Not only in the creation of expressive **form**, but also in the character of its **surface** textures and in the properties of its material **composition**. Kenneth Frampton would characterize it as a poetic consistency between a form and its construction [2]. Examples such as the freeform thin shells of Felix Candela, the textured concrete surfaces of Paul Rudolph and the exposed inner

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compositions and colored concrete of I.M Pei, represent the past relevance of these three tectonic dimensions in concrete.

Therefore, when examining the impact of digital fabrication technologies in concrete architecture, it is important to consider not only the possibility to overcome existing building limitations but also to unveil the emerging possibilities in those three tectonic levels. Within this framework, both technical and tectonic, this work seeks to answer the complex question: How can digital fabrication technologies expand traditional concrete architecture in form, surface and composition, through economically viable, sustainable and tectonically relevant methodologies.

To answer this question, this paper will be developed in two main sections. In the first, the authors perform a critical analysis on existing digital fabrication strategies, focusing on understanding how their application is shaping concrete architecture and concluding on the main challenges facing their widespread adoption. In the second section, the authors put forth a case for Robotic Hot Wire Cutting (RHWC) as a viable and tectonically relevant digital fabrication method capable of overcoming this condition.

2 Digital Fabrication Technologies in Concrete Architecture

Over time, the multifaceted nature of concrete and its complex production process has been a fertile ground for new material expressions, which are framed by existing production technologies and processes. With the recent dissemination of digital design and fabrication technologies, the production of concrete is facing new design opportunities. The most visible impact is related with the possibility for embracing design customization and complexity in concrete architecture. Towards this end, several digital fabrication processes have been developed.

2.1 Evaluating Existing and Emerging Solutions

Contemporary construction methods for complex concrete architecture are today still largely dependent on manually produced, customized formwork or CNC milled, Expanded Polystyrene (EPS) molds. Nevertheless, several other solutions have been developed that take advantage of digital fabrication technologies, either already in use in industrial settings or proposed in academic research prototypes. Such technologies can be broadly distinguished by their application for formwork production or in the direct production of concrete structures. In the following chapters, we provide a critical analysis of the most relevant technologies, focusing on their current and potential applications.

Digital Fabrication of Formwork for Concrete. The production of customized formwork for complex concrete architecture has been one of the main goals for the integration of digital fabrication technologies in concrete construction.

Subtractive Processes. The first applications of digital fabrication in concrete employed the capabilities of CNC (Computer Numeric Control) cutting or milling, to produce complex curved formwork from materials such as wood or EPS. CNC cutting

of wood panels was used in works such as the Mercedes Benz Museum (2006) and the Rolex Learning Center (2009) to achieve moderately curved geometries with smooth finishes, while still largely dependent on manual labor for assembly [3, 4]. On the other hand EPS foam molds have been produced through the use of CNC milling technologies or, more recently, with RHWC processes. While the former is capable of producing complex freeform geometries, having been thoroughly explored and optimized for 5-axis robotic technologies in the recent TailorCrete Project [5], RHWC is still mainly suitable for the production of ruled geometry. Nevertheless, it is regarded as a materially optimized and economically viable alternative to CNC milling for the production of EPS molds for concrete [6, 7].

Subtractive digital fabrication strategies for formwork production have been adapted to both in-situ and precast applications. In the first case, generally in the form of monolithic freeform constructions, such as the Spencer Dock Bridge by Amanda Levete Architects [8]. In the second case, oriented towards the production of complex assemblies of discrete elements at smaller scales such as the case of the interior precast panels of the Louisiana Sports Hall of Fame by Trahan Architects [9].

Formative Processes. An alternative approach to subtractive processes in mold production is to use formative processes through digitally controlled, reconfigurable molds with pin actuated systems, also developed in TailorCrete Project and several institutions [10, 11]. While benefitting from high adaptability, reusability and surface quality, these technologies are generally restrained to the production of surfaces similar to 3-axis milling and further limited to specific sizes and perimeters of the mold systems and to limited fabrication times when considering the need for multiple production runs. As such, examples of these systems currently show a tendency towards the prefabrication of double curved and high quality paneling systems [12].

Additive Processes. Although most commonly seen as direct concreting strategies, additive fabrication has also been explored for the production of molds for concrete. In these cases, 3D printing technologies are used to produce large quantities of differentiated molds in materials such as wax, sandstone and plastics [13, 14]. Although also limited to the size of printing systems, these solutions, benefit from the increased geometric freedom of 3D printing when compared to subtractive processes, particularly in the case of sintering or binder jetting. This makes them primarily suited for small-scale prefabrication of highly complex and differentiated components such as those resulting from the design of topological optimized structures [15].

Digital Fabrication of Concrete Structures. The direct production of concrete elements bypassing the need for formwork has been explored mainly through the use of additive technologies. Although some experiments have been developed using subtractive technologies (e.g. Robotic Diamond Wire Cutting) for the production of voussoir assemblies directly on cured concrete, these processes have been more suited for other materials such as stone [16].

Additive Processes. To date, several 3D concrete printing processes have been developed in academic and industrial settings. These cases use either an extrusion process where a digitally controlled nozzle deposits wet concrete in a layered process (e.g. Contour Crafting, Freeform Construction) or a binder jetting process, where a

binder solution is deposited on a powdered matrix, curing layer by layer (e.g. D-Shape, Emerging Objects). While binder jetting processes have the ability to produce extremely complex geometries, including voids and cantilever sections, extrusion processes are much more limited in possible shapes, considering the need for each layer to be supported by the previous one. As such, 3D printing of concrete structures has diverging results when considering different scales and methods. These range from small to medium scale assemblies of complex and customized elements, such as the case of the 3d printed beams developed at ETHZ [17], to large scale constructions with constrained geometries, like the prototype houses printed by the Chinese company WinSun [18]. Other strategies have also been developed that use additive technologies in optimized yet highly constrained and design specific processes, such as the robotic slip forming technology developed at the ETHZ for the production of column-like structures [19].

2.2 Expanding Form, Surface and Composition

Although not exhaustive, the previous analysis presents a large picture of what is today technologically feasible. At the same time, the different applications of such contrasting processes also point to emerging tectonic qualities of concrete structures produced with digital fabrication processes. These can be expressed as an expansion of the previously mentioned concepts of form, surface and composition in concrete.

Complex Double-Curved Geometries and Variable Modular Components. When considering the issue of form in digitally fabricated concrete architecture, we can identify two overall themes patent in the already mentioned examples of the Spencer Dock Bridge and the Louisiana Sports Hall of Fame: (a) double-curved surfaces in monolithic structures; (b) small to medium-scale assemblies of complex and customized components. As seen in the previous analysis, while the first is achieved mainly through the use of subtractive processes for formwork production, the second typically concerns prefabrication with additive and formative technologies.

Process-Driven Surface Textures. Although the capabilities of CNC milling and 3D printing have made possible the design and production of virtually any textural effect desired, digital fabrication processes in general have the potential for the creation of new and tectonically relevant process-driven surface textures. Milling paths, hot wire cutting marks and 3D printing layers are recurring traces in digitally fabricated concrete structures that have already been explored as aesthetic expression. For instance, the Building Academy Extension by SOMA Architects, where CNC milling toolpaths were explored as surface textures in cast concrete [20].

Variable Material Compositions. A common denominator in the use of digital fabrication technologies in general and in additive fabrication processes in particular is the relevance of the material composition, usually as a technical consideration. While concrete is traditionally cast in homogenous compositions, the use of digital fabrication processes such as multi-material 3D printing is also empowering the use variable concrete compositions in concrete. Such processes hint at materially optimized structures [21] and interesting new design possibilities that explore gradation in different

material properties, such as density and color [22], opening new design spaces for concrete architecture.

2.3 Critical Issues for Digital Fabrication in Concrete

The previous analysis shows a wide range of digital fabrication processes and the possibility expanding traditional concepts of form, surface and composition in innovative solutions for concrete architecture. Nevertheless, digital fabrication technologies still present critical issues that should be addressed to further their implementation into practice.

One major issue is the balance of geometric freedom, with production and material optimization. Being the most used digital fabrication solution for customized concrete architecture, this issue is particularly relevant in the case of CNC milling of EPS molds. Although CNC milling is a useful process for the production of complex and customized formwork solutions, it is also severely limited when considering three key aspects:

1. **high production times** resulting from the high-resolution milling process necessary for smooth finishes;
2. **low material optimization and sustainability**, considering the large quantities of material discarded as waste for each mold surface produced through milling, when compared with the potential absence of waste from hotwire cutting.
3. **high overall production costs,** from materials, labor and fabrication times.

Based on these issues, CNC milling of EPS molds is usually considered a cost-ineffective process only suitable in works of exceptional character and budgets, with particular complex geometries. This issue was apparent in the recent case of the Waal Bridge Extension by Zwart & Jansma, realized with traditional, manually produced wood formwork despite its freeform geometry, considering the high costs inherent to CNC milling [23].

A second relevant issue is the adaptability and integration of digital processes into the construction industry. Processes such as 3D printing of molds and finished structures present substantial improvements in sustainability by eliminating waste production. Although potentially disruptive, these processes require highly technological setups, more suited the controlled environments of prefabrication and laboratory settings. Their application in the construction industry is therefore not easily fulfilled in current industrial contexts, requiring the transformation of existing processes, methodologies and equipment, limiting the possibility for their adoption and widespread use.

Considering these critical issues and the emerging design opportunities of digital fabrication, in the next sections we present a case for RHWC as a viable and tectonically relevant digital fabrication technology for concrete architecture.

3 A Case for Robotic Hot Wire Cutting

3.1 Description

RHWC is a recent evolution of wire cutting processes already found in industrial and pre-industrial settings [24, 25] and used for the fast carving of large volumes of materials such as clay, wood, stone and more recently EPS foam. Later industrial developments have paired this tool with different automation mechanisms such as 3 and 4 axis CNC gantries. In the case of current RHWC systems, a thin heated wire is stretched in an end-effector, attached to a digitally controlled 6-axis robotic arm and used to cut through solid EPS blocks, producing molds for concrete casting. The main features of this process are its overall speed (when compared with CNC milling) and its inherent limitation to the description of ruled surfaces, resulting from the movement of the hot wire through the EPS material. As such, RHWC is applicable mainly in the production of such surfaces or in the approximation of more general double-curved designs which have been rationalized to fit the ruled surface criteria [26].

In the research field of architecture, RHWC has seen several developments in the last decade, with experimental works such as the Periscope Tower, the RDM Vault [6] and the Opticut prototype [16], exploring the design potential of RHWC. More recent developments are focusing on overcoming the geometric limitations of ruled surfaces through the exploration of flexible blades and multiple robot setups, allowing for the direct creation of more general double-curved surfaces [23, 27].

These and other experiments have suggested that RHWC can address the most critical issues described in Sect. 2.3, proposing a fast and cost-effective digital fabrication strategy for the production of formwork for concrete architecture.

To understand the potential of RHWC and explore this technology, two case studies were developed, focusing on different technical and design aspects of RHWC and with a specific interest in the development of mold design and production solutions for prefabricated concrete architecture.

3.2 Ruled Concrete Panels

The Ruled Concrete Panels experiment was developed as a primary exploration into the techniques and processes of RHWC. Its main objectives were to evaluate the limitations and potentials of this technology for the fabrication of customized concrete molds. For this purpose, a set of interlocking elements was designed, based on the geometry of typical precast panels for mechanically stabilized earth systems (MSE). This particular geometry was projected onto a hyperbolic paraboloid surface, resulting in a set of double curved ruled panels, suitable for RHWC. With this arrangement, three challenges were identified and used as specific objectives for the ruled panels case study:

1. **Form** - addressing the geometrical constraints of RHWC;
2. **Surface** - exploring process specific surface textures in RHWC;
3. **Composition** - exploring the possibility of variable concrete composition through mold design.

Case Description. Each panel addressed one of the highlighted challenges. Panel 1 was designed as a control, addressing only geometrical issues. Panel 2 was used for exploring ruled surface textures. Panel 3 employed a variable composition through a layered casting process. With these objectives in mind, the molds were designed specifically for the RHWC process. Each was composed of 3 stacked parts, defining a front surface, a back surface and an interior perimeter (see Fig. 1b). The mold for Panel 3 featured an intermediate subdivision to enable the layered casting required (see Fig. 1c). Using this strategy, the complete molds were cut from 1000 × 500 × 350 mm EPS blocks in a sequence of sweeping cuts, defining each respective surface.

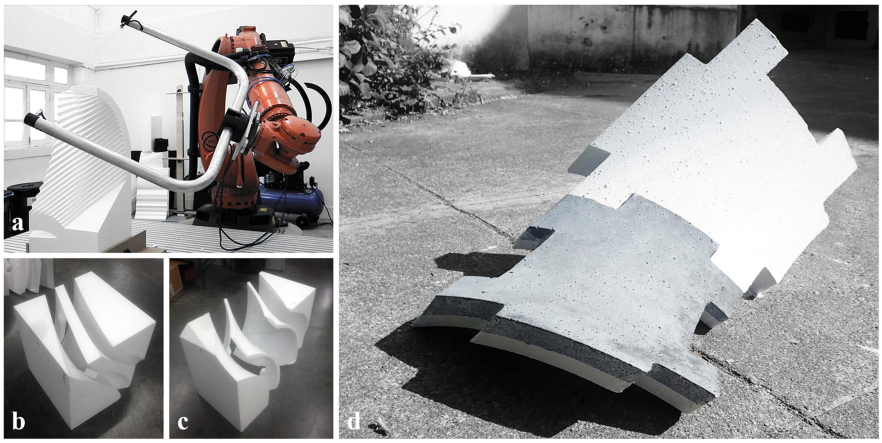


Fig. 1. (a) RHWC fabrication process for textured panel 2; (b) EPS mold for panel 1 (c) EPS mold for panel 3; (d) final assembly of panels 1 and 3, featuring layered concrete composition.

During this process, we identified several key constraints and characteristics of this technology, regarding aspects of speed, precision and geometry. The relation between speed, temperature and the resulting cut width (kerf) was a fundamental parameter. After initial runs, a relatively low speed and temperature were defined to improve accuracy and to avoid excessive melting in specific areas such as ridges and corners which after casting would have compromised the assembly of the finished components. Although a conservative speed was used, each cutting sequence was completed in approximately 7 min, without significant increases in the more complex, textured mold surfaces or the subdivided mold of panel 3.

After assembling and bracing the molds to withstand the concrete pressure, they were cast with a mix of self-compacting concrete, reinforced with polypropylene fibers. For the variable composition panel, different colored mixes were cast in two phases, separated by a 24 h period. After curing, the panels were easily demolded by separating the mold layers. A more thorough description of this experiment and its findings can be found in Martins et al. [28].

Case Conclusions. One of the main advantages proposed by RHWC was that of increased speed and material optimization. As was verified in this case study, the increased cutting area of a line vs. a point (as in milling or 3D printing) allowed for a drastically improved processing time, several orders of magnitude faster than most subtractive or additive processes.

The material optimization inherent to RHWC was also demonstrated with this work. The preservation of material volume after each cut eliminated the production of waste (from transformation) and opened the possibility for the use of successive cuts in the layered mold strategy. This had the effect of halving the required material volume in comparison with typical milled EPS formwork. When combined, these factors greatly decrease production times and costs, increasing the overall economic feasibility and sustainability of this technology.

Regarding surface quality, although the produced surfaces were not smooth, we found that the ruled textural effects produced through RHWC had an interesting aesthetic and tectonic potential, describing a visual relation between the RHWC process and the design of the ruled surfaces.

Finally, the layered mold strategy enabled by the RHWC process also opened the possibility for more complex mold assemblies, allowing for the combination of different material compositions in one single component.

3.3 The CorkCrete Arch

The CorkCrete Arch was developed as an application and expansion of the previously explored strategies and methods, testing them in a full-scale design prototype. Other specific objectives were also addressed in the scope of this project:

1. Testing RHWC processes in large-scale geometries
2. Testing the layered mold strategy in an industrial environment
3. Testing the integration of RHWC with other processes and materials
4. Testing the precision of RHWC in large-scale assemblies

Case Description. To achieve these objectives, the CorkCrete Arch was developed as a composite system, composed from the assemblage of 3 structural Glassfibre Reinforced Concrete (GRC) elements and 18 cork panels. Its geometry was defined to challenge the RHWC process, featuring an interior creased surface resulting from the intersection of 2 ruled surfaces and a lateral face of variable width (see Fig. 2d). These features became the central geometric challenges for the RHWC process.

The design of the molds for the 3 GRC panels followed the same layered strategy employed in the previous case with few exceptions. To overcome the proposed geometric and size challenges, each mold was divided in two halves through their longitudinal axis, prior to fabrication. Each mold half was cut in a sequence of 4 hot wire cuts plus one milling operation, combining the advantages of both processes. Similarly to the previous case study, each cutting sequence was completed in approximately 10 min, illustrating a slight increase in time, consistent with the increase in cutting area. The finalized molds were shipped to a precast facility and used for the production of the final components through a normal GRC spray-up procedure. Once completed, the



Fig. 2. (a) Hot wire cutting of mold with interior ruled surface exposed - center component; (b) GRC spray process after assembled mold – center component; (c) finished GRC center arch component; (d) final assembled Corkcrete Arch.

CorkCrete Arch was manually assembled with success in several different settings, attesting to the accuracy of the fabrication process. The RHWC mold fabrication and GRC casting process for the Corkcrete Arch experiment was fully described in Sousa et al. [29].

Case Conclusions. The layered mold strategy confirmed, once more, the material optimization and speed advantages of RHWC, in this case, in the context of large-scale elements. Furthermore, the mold fabrication strategy proved to be successful in accurately reproducing the complex geometry of all the contact faces between GRC panels as well as GRC-cork interface surfaces.

This case study also revealed that a thoughtful consideration of formwork subdivision can be used to address specific geometrical challenges, increasing the design possibilities of RHWC. Additionally, since these subdivisions became imprinted on the finished surfaces, an interesting aesthetical relation between design and fabrication process was developed.

In terms of adaptability and integration, as already stated, RHWC can be used for the production of molds for prefabrication or in-situ construction by combining formwork sections as was the case in the CorkCrete Arch. In both these contexts, the production process and outputs were demonstrated to be easily integrated in industrial settings, without the need for specific equipment or procedures.

4 Conclusion

This paper presented the question “How can digital fabrication technologies expand traditional concrete architecture, through economically viable, sustainable, and tectonically relevant methodologies?” To address this question, a specific digital fabrication technology was proposed and two case studies were developed.

Through these experiments, RHWC proved to be able to overcome the main critical issues facing digital fabrication in concrete, having a large set of advantages in comparison with other processes, balancing its main geometrical drawback. Most notably, RHWC allowed for a significant decrease in fabrication times, combined with high material optimization and sustainability, making it an optimal solution for the production of formwork. Furthermore, considering the issue of adaptability and integration, RHWC processes and outputs were found to be easily adapted to the industrial context without the need for exceptional considerations. Although clearly limited in terms of geometry, we believe that RHWC still holds potential regarding this subject for three main reasons:

- ruled geometry is still significantly relevant today as an architectural language;
- when compared with traditional means, 6-axis robotic strategies greatly increase the variability and geometric freedom within the realm of ruled surfaces;
- ruled geometry can also be used to rationalize general double curved surfaces, increasing its relevance in architectural practice.

In light of this research, we also believe that Robotic Hot Wire Cutting is a process with great tectonic relevance. Being constrained to an intrinsic formal vocabulary opens the need to consider the fabrication strategy at an early design stage. This fact results in tectonically interesting solutions with a strong relation between the design and fabrication processes. This aspect became clear in the overall design solutions tailored by the RHWC process which impacted in all three tectonic dimensions of form, surface and composition. In addition to the already mentioned ruled vocabulary, the process-driven design of surface textures extracted directly from the RHWC process and the layered mold strategy enabling composite material compositions all contributed to establish specific tectonic qualities of digitally fabricated concrete through Robotic Hot Wire Cutting.

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RETHINKING THE PHILIPS PAVILION THROUGH ROBOTIC HOT WIRE CUTTING.

An experimental prototype

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The Philips Pavilion by Le Corbusier and Jannis Xenaquis was a landmark project in thin shell concrete construction, only made possible by an experimental precasting strategy that deeply defined the architectural character of the hyperbolic paraboloid surfaces of the pavilion. Using this historic precedent this research presents a reinterpretation of the design of the Philips Pavilion, specifically tailored for Robotic Hot Wire Cutting technologies and a layered mold system, combining speed and material optimization towards more sustainable concrete construction processes. By documenting the realization of an experimental prototype at a 1:2 scale, this paper demonstrates the feasibility of the proposed strategy and its value in comparison with existing construction scale digital fabrication technologies for concrete.

Keywords: *Digital Fabrication, Concrete, Robotic Hot Wire Cutting, Philips Pavilion*

INTRODUCTION

Background

In the second half of the XXth century, several remarkable concrete thin shell structures were built, featuring curved geometries of increasing complexity. Such structures were built mostly through analogic and empiric design and construction processes, which not only were complex and costly, but also imposed significant design constraints and sustainability issues, particularly in the production of the necessary scaffolding and formwork for their realization.

One such example was the Philips Pavilion, designed by Le Corbusier and Yannis Xenaquis for the 1958 World Exhibition in Brussels, featuring a set of extremely curved hyperbolic paraboloid surfaces. The pavilion's construction was, at the time, only made possible through an unconventional construction process. The selected strategy used hand-made sand molds for the prefabrication of approximately 2000 rhomboid concrete panels composing the 9 ruled concrete surfaces of the pavilion (Duyster 1959) (Figure 1).

Although ultimately successful, it was an expensive and labor intensive process, imparting specific design constraints on the architecture of the Philips Pavilion. Notwithstanding the great commercial success of the pavilion, it was demolished soon after the exhibition ended.

Subsequently, there has been some research pointing to strategies for rebuilding the Philips Pavilion using modern construction technologies, which generally dismiss the original prefabricated subdivision strategy that gave it its character, for more efficient construction strategies. Methods such as in-situ concreting, large prefabricated shells and sprayed concrete using membrane formworks can be found in existing literature (Pronk 2007; Nijse 2008). Although as of yet there hasn't been an actual reconstruction of the pavilion, these demonstrate not only the continuing architectural relevance of the Philips Pavilion but also the challenge that erecting such a structure still presents today.

During the last decade, the increased demand for complex concrete structures stemming from the development of digital design and fabrication technologies has been accompanied by an increased awareness for the issue of sustainability in construction. Though several new methods for the production of freeform concrete surfaces have been developed that could be effectively applied to a potential reconstruction of the pavilion, the production of such large-scale and complex constructions still present economic and sustainability problems with design consequences that should be addressed within the field of architectural research.

Objectives

This paper proposes to address these issues by rethinking the construction of the Philips Pavilion through the use of tailored digital fabrication technologies for the production of complex ruled surfaces. Considering the ruled geometry of the pavilion and the original precast strategy, we believe that Robotic Hot Wire Cutting (RHWC) can not only improve the efficiency and sustainability of the construction process, but can also introduce new possibilities in the design of the pavilion, maintaining the tectonic link between construction and design that was already present in the original work.

Within this framework, the work presented in this paper focused on 2 main goals:

- **develop a layered formwork strategy** tailored for RHWC, based on the sequential cutting of large Expanded Polystyrene (EPS) blocks, optimizing material usage and production processes, while maintaining its economical and industrial viability.
- **define and explore a new design space** for the pavilions' panel geometry, emerging from the properties of this digital fabrication process and the geometrical needs of the mold strategy.

STATE OF THE ART

Current industrial formwork solutions for freeform concrete

Contemporary industrial solutions for the construction of complex curved geometries in concrete generally depend on CNC cutting and milling technologies for formwork production of either in-situ or precast structures. Such technologies can be employed in manually assembled wood formwork, using precut elements such as guides, templates or entire formwork sections. Examples of works using this strategy can be found in the Rolex Learning Center (SANAA, 2009) and the Waal Bridge Extension (Zwart & Jansma, 2015).

Large-scale, multiple-axis CNC milling can also be used in the production of EPS (expanded polystyrene) foam molds either as inserts in traditional in-situ formwork systems, as was the case of the Spencer Dock Bridge (Amanda Levete, 2009), or as stand-alone molds for precast components, as seen in the Zollhof Towers (Gehry, 1999) and, more recently in the Louisiana State Museum (Trahan Architects, 2013).

Although CNC milling still presents important

Figure 1
Philips Pavilion (1958); sand mound formwork for ruled surface panels (1957)



advantages for the production of complex and customized formwork (i.e. its geometric freedom and versatility), it also presents several drawbacks. The need for smooth casting surfaces and the inherently slow process of incremental subtraction of material that defines CNC milling result in its two major disadvantages: 1. overall high machining times and costs and 2. large volumes of consumed and wasted materials. Considering these drawbacks, CNC milling is usually reserved for works of exceptional character and corresponding budgets, such as the ones previously mentioned.

Alternatively, the use of Robotic Hot Wire Cutting (RHWC) of EPS foam blocks for the production of concrete molds has been explored in several academic prototypes and has also been tested in large-scale commercial implementations, such as the in-situ formwork for Kirk Kapital Headquarters (Olafur Eliasson, 2018). For the exclusive production of ruled surfaces in concrete, RHWC has now been generally demonstrated as a viable alternative to CNC milling with reduced costs, operation times and waste volumes (Søndergaard 2017). More recent developments are now focusing on technological improvements, such as multiple robot setups and more flexible end-effectors such as hot-blades and abrasive wires (Søndergaard 2016).

As its still far from a broadly accepted process in industry, the authors believe that there is still room for increased sustainability, optimization and exploration of RHWC in relevant case studies. Particularly, this research aims to shift focus from the development of technological tools, to the exploration of specific molding processes related to RHWC and their potential impact on the constructive and architectural aspects of the Philips Pavilion.

RETHINKING THE PHILIPS PAVILION

In order to assess the possibility of rebuilding the complex concrete surfaces of the Philips Pavilion through the use of a tailored robotic fabrication process and mold strategy, an experimental prototype was devised which will be documented and discussed in this section. After consideration of the 9 hyperbolic paraboloid surfaces composing the pavilion, one was selected as a case study for this research (figure 3.2). From it, new subdivision designs were explored and production, using a layered mold strategy, was compared to a CNC milling scenario. Finally, a prototype consisting of a 1:2 scale section, composed of 9 50x50x5cm precast micro-concrete panels was built, through the use of Robotic Hot Wire Cutting.

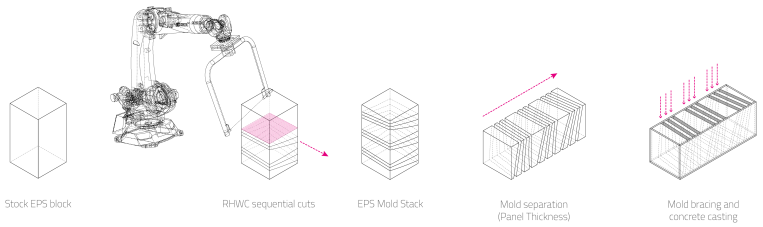


Figure 2
Layered mold design logic for RHWC

Layered Mold strategy for RHWC

The logic of layered or stacked molds for concrete production is not an entirely new process. In academia, there have been examples of the use of similar logics, applied to concrete, using different fabrication processes (Enrique 2016) or directly to other materials such as ceramics (Mankouche 2012). In the precast industry there is also the specific precedent of mold batteries for the large-scale production of identic flat, double-sided concrete panels. The central aspect of this logic in all cases is that elements can be cast (or cut) side by side, with one side of one element being coincident with another side of the next. This logic can be particularly relevant when used in conjunction with RHWC.

One of the main advantages of RHWC over traditional subtractive technologies (i.e. milling) for mold fabrication in foam like materials (EPS) is the preservation of excess material when cutting a surface. Although this feature is a staple of RHWC, the general usage of such molds has been similar to other subtractive processes - one section per mold. An alternative to this logic is the creation of successive cuts, subdividing a stock EPS block into several layers. Applying this concept to mold design allows for the creation of a layered mold of stacked pieces with varying geometry, from one single block of stock material.

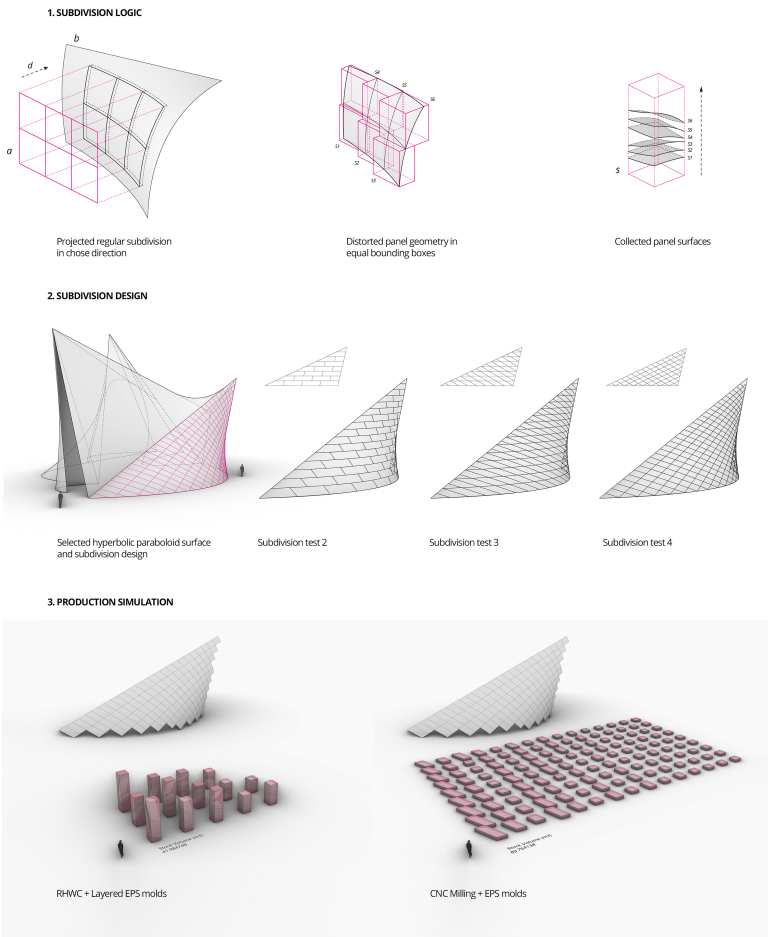
Depending on the shape geometry and the positioning of a panel surface within the stock material, this process can be optimized for a minimum of 1 cutting operation per panel surface, foregoing the need for perimeter cuts, if all edges of the panel geometry are coincident with the stock material sides. If this condition is met, the mold layers can then be separated with a specific distance, leaving voids to be cast with concrete (figure 2).

Surface design for RHWC and a layered mold strategy

The original panel design for the precast panels of the Philips Pavilion was constrained by the necessity of having panel boundaries following the ruling directions of the overall ruled surface. This was imperative for workers to have straight wood guides for the manual description of the ruled surfaces of each panel. Using these guides and an underlying sand mound (also molded following surface rulings), the workers could cast concrete in the subdivided voids and accurately describe the necessary panel geometry with simple wood beams (Duyster 1959).

In the layered mold strategy developed in this work the relevant geometrical constrain is the coinciding projection of the panel surfaces within a boundary volume. With this fabrication logic in mind, a geometrical process was developed for designing viable paneling subdivisions that could be subsequently grouped in a vertical stack with coinciding edge projections. This was achieved simply through the projection of a regular tessellation (a) onto the ruled surface (b), in a specific direction (d) (figure 3.1). Using this process, the shape of the tessellation dictates the stack section geometry (ex. square), while

Figure 3
Surface subdivision logic; subdivision design studies; RHWC and CNC Milling comparison



the projection direction dictates the panel's shape on the surface and its fixed position inside the stack.

This strategy established from the onset a different possible vocabulary for the pavilion surfaces, in line with the existing architectural logic of prefabrication but with an expanded design space featuring a new set of guiding principles and rules, directly linked to this digital fabrication strategy and not limited by the ruling directions.

Using this method, the surface subdivision was explored in several solutions, tailored for different purposes. Goals such as panel size and curvature (large vs small), projected shape geometry (square, rectangular, losangular, triangular) and boundary variation minimization (recursive subdivision) were explored (figure 3.2). On a design note, considering the original strict subdivision that exacerbated the rulings of the parabolic hyperboloid geometry, in this reinterpretation the authors favored solutions with evidently curved boundaries.

Within these parameters, a solution was chosen that combined the ease of production of regular square section EPS material blocks with ruled panel boundaries in one direction and curved boundaries in another direction, emphasizing the curvature of the ruled surface and distinguishing it from the original ruled subdivision (figure 3.2).

To simulate and evaluate the production of the selected solution, a simple algorithm was developed that automated the grouping (along ruling directions) and translation of the 135 individual panels into stacks of 10 panels each, with a minimum separation of 10cm between panel surfaces to ensure a suitable EPS thickness for the molds. No further optimization of distribution and nesting was attempted.

The entire process was evaluated and compared to a CNC milling scenario of individualized molds. For this purpose, it was equated that the CNC milled molds would be tailored for minimization of milled height and the panels were situated in the stock material with this consideration, including a minimum of 20cm of EPS height for stabilization and an offset of 5cm for boundary walls. This resulted in 14 stacks for the case of the layered molds and 135 individual elements for the case of CNC milled molds. Analyzing the results for material volume, the first case revealed an expenditure of approximately 42 m2 of EPS, in comparison with approximately 89 m2 for the same surface area in the CNC milling scenario (figure 3.3).

Robotic fabrication and concrete production process

After scaling down the selected prototyping area of 3x3 panels to a 1:2 scale, the same grouping and surface translation process developed earlier was employed for a stock material geometry of 50x50x100cm EPS blocks (figure 4).

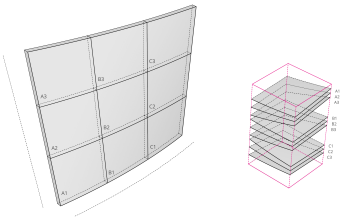


Figure 4
Prototype panel model; Cutting surfaces in stack

For the robotic production of the molds, simulation and toolpath generation was done in Grasshopper for Rhinoceros, using the Kuka|prc plugin. The prototype stack was cut using a 6-axis Kuka KR 120 industrial robot, equipped with a large-scale hot wire end-effector and a maximum cutting width of 85cm. The cutting sequence was completed in a straightforward process of 10 cuts, one per surface, without any issues arising from this process. The entire sequence was concluded in approximately 15 minutes, corresponding to the relatively slow speed (aprox. 1cm/s) and temperatures used to ensure correct cutting geometry.

For the construction of the molds, the layered stack was placed sideways, separated with the desired panel width (5cm) and assembled inside a form-



Figure 5
RHWC EPS stack after cutting process; Assembled test prototype from mold parts.

work plywood shell, leaving the voids to be poured with concrete. The plywood shell was closed and clamped, leaving the top side open for vertical casting in the voids left by the EPS elements. After initial experiments, this mold design was improved with 2 fixed subdivisions, dividing the panels in groups of 3 to increase EPS resistance to concrete casting pressures and prevent any buckling from occurring inside the molds. (figure 6)

In preparation for the casting process, no post-processing was done on the EPS surfaces and a simple coating of demolding oil was used to ensure a correct casting and demolding of the panels and to minimize the overall production time and costs.

Considering the closed mold design with the desired panel geometry and the difficulties of vibrating and applying regular reinforcement meshes, a self-compacting concrete mix was used, consisting of grey Portland cement, fine aggregates and fillers, combined with polyprolylene fibers for reinforcement.

Concrete pouring was executed sequentially, in groups of 3, in order to further prevent differences in pressure inside the individual voids and minimize the lateral pressure of the concrete on the EPS molds parts. The panels were demolded after 8 days of curing time and assembled in their final disposition, confirming the desired geometry of the Philips Pavilion prototype.

DISCUSSION AND CONCLUSIONS

In the development of the described research, different constraints and characteristics of the proposed process became apparent that are discussed here, before conclusions are drawn.

Regarding the geometric constraints of the layered strategy and required design, some consideration should be taken in selecting the projection direction of the subdivision in order to avoid excessively vertical panels inside the stock material and optimize material usage. Also, the process assumes (as the original construction method), that the panel sides are not perpendicular to the surface curvature. This evidently prevents its usage in stereotomic assemblies, where such characteristic is fundamental, without using variable section stacks. These inherent constrains clearly position this strategy between the complete dependency on ruled boundaries of the original casting solution and the complete geometrical freedom of the CNC milling process. Moreover, although the non-square EPS blocks necessary for some of the studied surface subdivision cases would

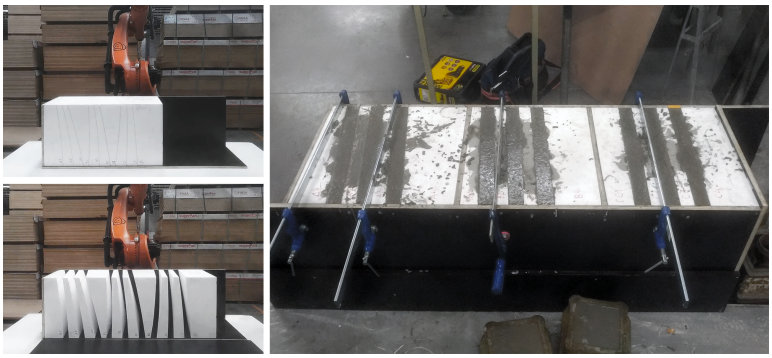


Figure 6
EPS mold preparation; closed mold after casting

complicate formwork design, the advantage of building the entirety of the ruled surface, using only 2 types of mold stacks could represent considerable benefits in terms of construction optimization.

Regarding the Robotic Hotwire Cutting, as discussed before, the process presented considerably reduced times when compared to normal CNC machining for the same surface area. Considering approximately 120min/m2 to 240min/m2 for CNC milling (depending on desired surface smoothness) and the extrapolation of 240s/m2 for RHWC, this represents a 30 to 60 fold decrease in fabrication time for RHWC. These times were somewhat offset by the added time and manual labor of assembling of the mold stacks into the plywood formworks, leading to consider the necessity of improving this stage of the process. Nevertheless, the increased output of the process in an industrial setting would mitigate this aspect and should not be comparable with full manual assemblies of wood and sand formwork of the original process.

As expected from previous experiments, the surface quality of the concrete panels (figure 7) was not comparable with precast panels using other strategies, such as regular wood formwork or molding tables using membranes, due to the EPS porosity. Nevertheless, improvement measures can be taken to achieve the same qualities, through the use of EPS coatings, without compromising the overall process. Moreover, the use of the closed molds with lateral panel sides facing the plywood panels, resulted in smooth and precise boundaries in the finished panels.

In conclusion, we believe that the RHWC process in conjunction with the layered mold system presents clear advantages to traditional mold systems and several other digital fabrication strategies. It leverages the speed and efficiency of Robotic Hot Wire Cutting with the ability to rationalize curved panel subdivisions to maximize production efficiency, thus attaining an increased sustainability by decreasing material volume waste by roughly 50% when compared with current milling strategies. At the technical level, other advantages can also be found, namely 1) the reduction of processing times (and output volumes per square meter), 2) transportation and storage costs (through volume optimization), 3) ease of integration with existing precast practices, without the need for other complex digital fabrication procedures. All such

Figure 7
Assembly of 4 finished panels



advantages represent important chances for an increased democratization of digital fabrication strategies in current construction practice.

Finally, past experiments in rebuilding the Philips Pavilion were mostly focused on the construction of continuous or (mostly continuous) hypar surfaces in concrete. While this was certainly a possibility considered by the original architects, we believe that the final built pavilion expressed a more nuanced story of technological innovation in precast concrete construction, which fueled the particular architectural expression and tectonic relevance of the Philips Pavilion.

At this architectural level, this research demonstrates a possibility of rebuilding the Philips Pavilion within this spirit, maintaining the original tectonic character of its ruled, prefabricated surfaces in a reinterpreted design, specifically for RHWC. On a broader scale, this research shows how digital fabrication technologies can be configured for enhanced sustainability and efficiency, while also driving architectural language in coherent tectonic expressions, maintaining strong relations between construction and design.

ACKNOWLEDGMENTS

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The architecture of slicing

Balancing automation, design and sustainability in digitally fabricated concrete through RHWC

Keywords
– Concrete, digital fabrication, robotic hot wire cutting, automation, sustainability

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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.

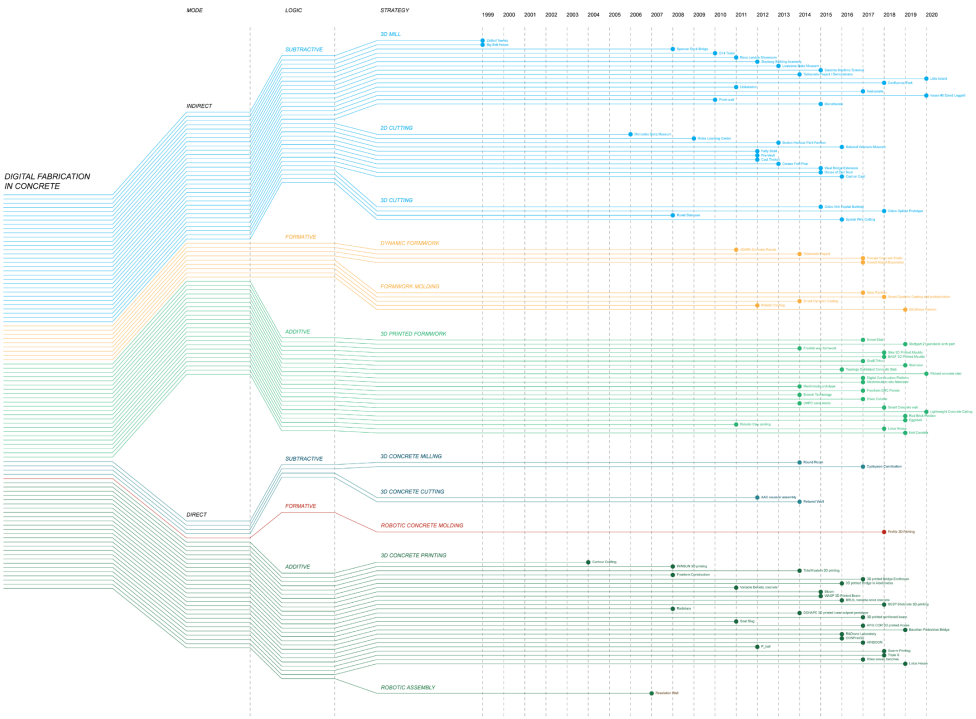


Fig. 1 Classification and timeline of different examples of digital fabrication strategies for concrete elements, using three parameters: intervention mode, transformation logic and technological strategy.

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*

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 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.

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.

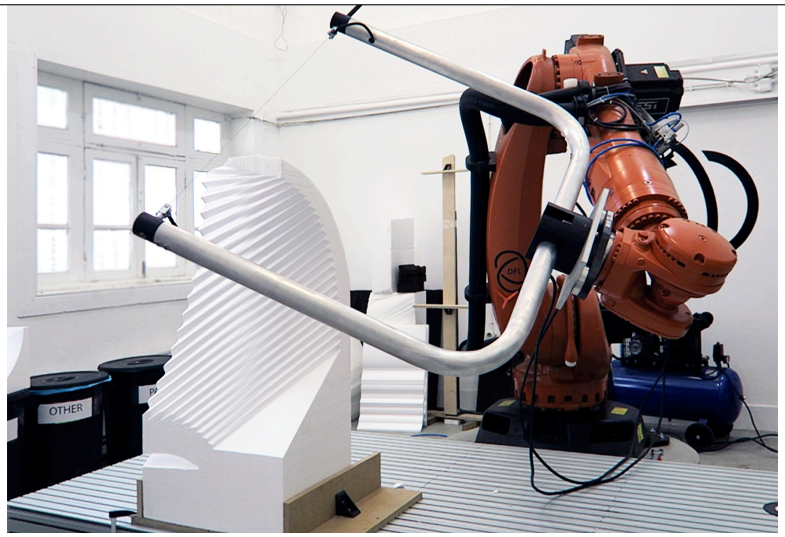
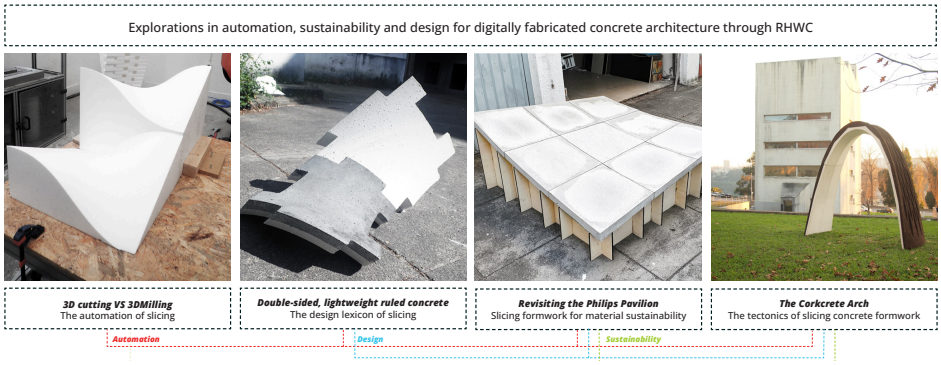


Fig. 2 The robotic hot wire cutting setup. A 6-axis Kuka industrial robot and a hot wire end effector tool.

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.



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

Fig. 3 Prototype A: RHWC vs 3D Milling;
Prototype B: MSE panels;
Prototype C: Revisiting the Philips Pavilion;
Prototype D: The CorckCrete Arch

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.

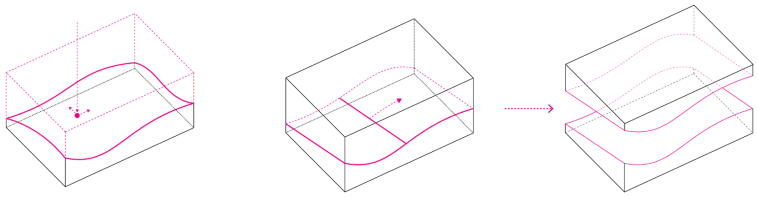
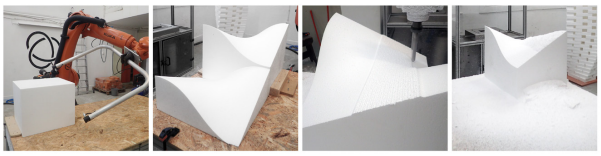


Fig. 4 The material transformation logics of 3D milling and 3D cutting.



	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.

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 m^3 of waste was produced from a starting volume of 0.6 m^3, 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.

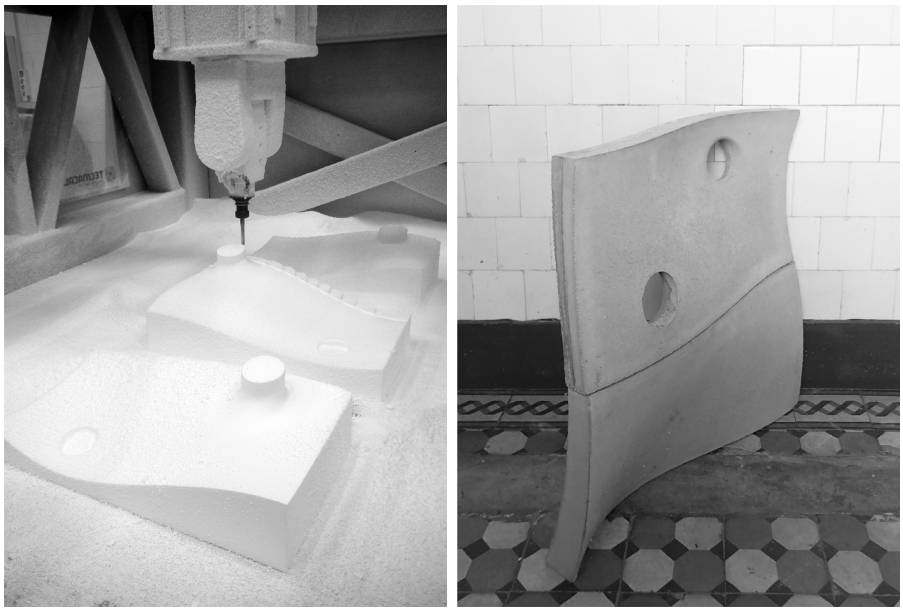


Fig. 6 Prototype A. 3D milled, customized concrete elements of variable double curved geometry.

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-weffective 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 Felix 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).

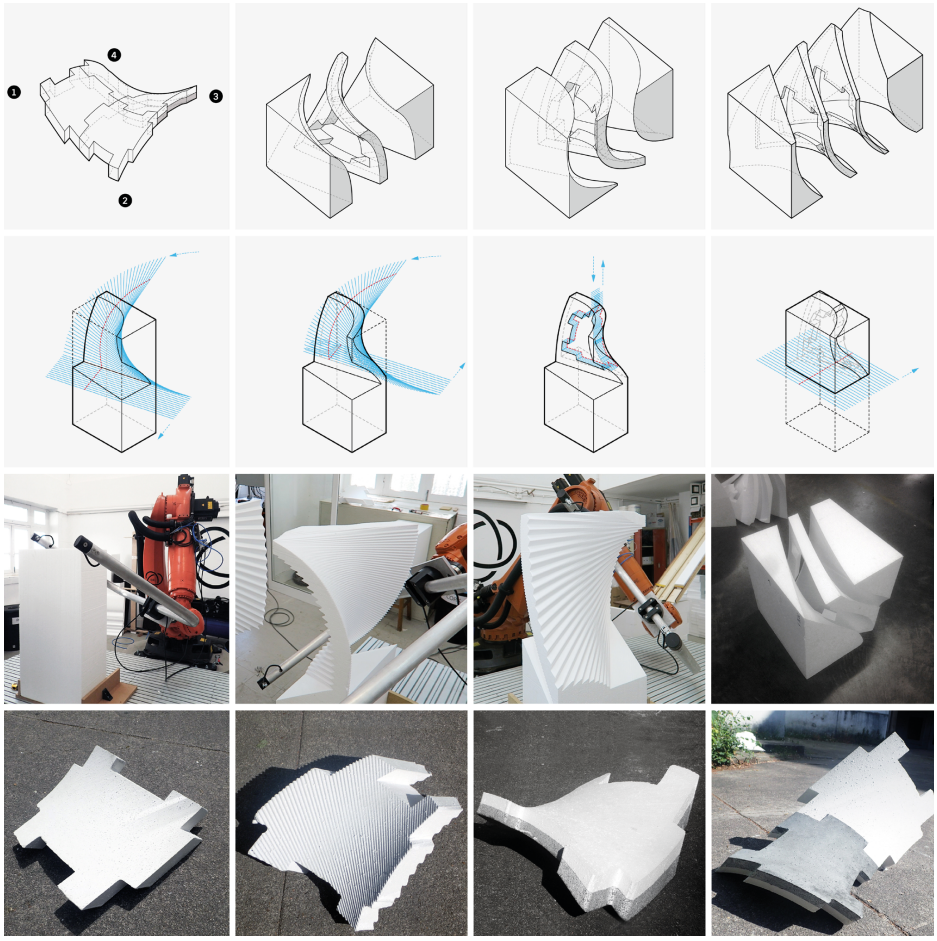


Fig. 7 Prototype B: The MSE Panels; (top to bottom rows) a) panel geometry and layered mould design for panels 1, 2 and 3; b) cutting routine for panel 4 (front cut, back cut, perimeter cut, bottom cut); c) RHWC fabrication process and final mould for panel 1; d) finished parts showcasing textured surfaces, variable compositions and two assembled panels.

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 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

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).

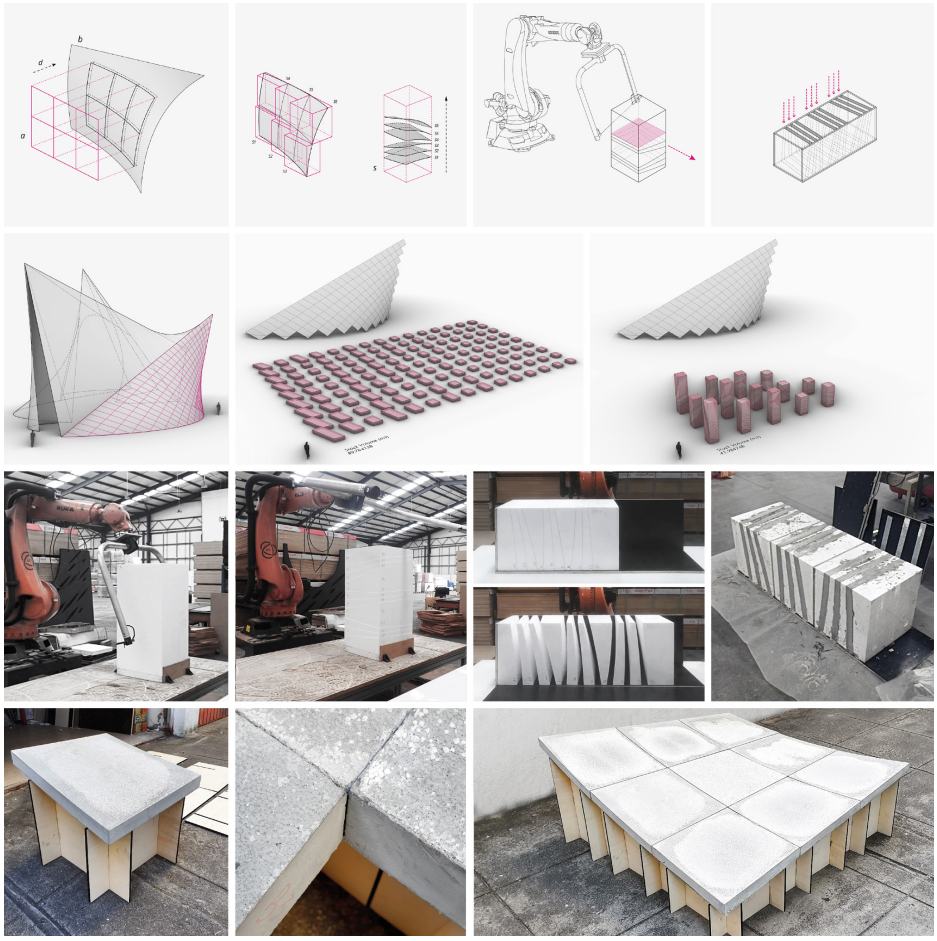


Fig. 8 Prototype C – Revisiting the Philips Pavilion; (top to bottom rows); a) panel stacking logic; b) subdivision and stock volume comparison for milling strategy and layered mould strategy; c) robotic hot wire cutting of a mould stack, mould assembly and cast panels; d) finished panel and assembled prototype.

panels. Its central feature is that multiple elements can be cast side by 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 Yannis Xennakis'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 m3 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).

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.

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

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.



Fig. 9 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.

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

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

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

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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Tectonics and Material Transformations
Exploring concrete in architecture through digital fabrication processes

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