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JOELHO

Journal
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Culture

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no. 14

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Digital Culture
What's Next?

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Colégio das Artes
Largo D. Dinis
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Portugal

w: impactum-journals.uc.pt/joelho
e: edarq@uc.pt
t: +351 239 851 350

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Armando Rabaça
Department of Architecture
of the University of Coimbra

Bruno Gil
Department of Architecture
of the University of Coimbra

Isabel Clara Neves
Centre for Studies in Architecture
and Urbanism, University of Porto;
Centre for Social Studies,
University of Coimbra

Digital Culture – a Plea for a Critical Future

Editors' Note

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We live in an era characterized by profound changes in the way we perceive and interact with the world, guided by the driving force of digital technologies, a phenomenon many authors have no hesitation in calling a Fourth Industrial Revolution. As diverse as these changes may be in the realm of architecture, they are inevitably embedded in a long-standing negotiation of formal codes, as suggested in Antoine Picon's *Digital Culture in Architecture* and Mario Carpo's *The Alphabet and the Algorithm*, ultimately leading Reinhold Martin to ask: "Is digital culture secular?"[1]

Despite the inevitable links with past codes, soft architecture technologies based on speculative intelligence are leaving behind what Nicholas Negroponte named "soft architecture machines," in which hardware still ruled, and opening a new era which is definitely distinct from the First or Second Machine Ages, as identified by Reyner Banham. Indeed, these digital changes are part of a deeper historical change. We are experiencing growing political instability on a global scale, in which social inequality is increasing while the worldwide urban population has surpassed the entire rural population. These phenomena have given rise to problems in urban policies, such as a lack of quality housing, social segregation, and the informal growth of cities. The evolving and nearly unavoidable phenomenon of climate change has been accompanied by

1 See Antoine Picon, *Digital Culture in Architecture: An Introduction for the Design Professions* (Basel: Birkhäuser, 2010); Mario Carpo, *The Alphabet and the Algorithm* (Cambridge, Mass.: The MIT Press, 2011), Reinhold Martin "Is digital culture secular?: On Books by Mario Carpo and Antoine Picon," *Harvard Design Magazine: architecture, landscape architecture, urban design and planning*, no. 35, (2012): 60.

a growing awareness of the effects of human activity on the planet and of the urgent need to achieve a measure of environmental sustainability. These changes all have direct consequences for the practice of architecture.

After reflecting in issue 13 on how memory can act as a catalyst for architectural thinking within the singular mind of the creative individual, the particular interest of this issue of JOELHO is in how shared and collaborative processes, driven by the architect operating within this digital culture, are motivating experimental architectural and urban practices in an attempt to confront the associated political, environmental, and social concerns. Apart from the digital turn advanced by rhetoric founded on aesthetic novelty or on innovative, conceptual ways of making, the undeniable strength of digital tools resides in how, and by what means, they might contribute to a more environmentally, politically and socially responsible architectural practice.

However, the long discussed suspicion over the digital world in architecture has been the menace towards hand-drawing and making. In 2012, the postmodernist Michael Graves questioned whether drawing is actually becoming a "lost art," when "digit" – meaning "finger" – has been replaced by "digital" – relating to data: "Are our hands becoming obsolete as creative tools? Are they being replaced by machines? And where does that leave the architectural creative process?"[2] An answer came precisely from the current new generation, reacting to the dull use of the digital trends of rendering and visualization, and arguing for a recovery of pre-digital "cut and paste" techniques, nevertheless with the use of digital tools. Sam Jacob contended this as a sign of a post-digital attitude driven by a similar modus operandi of the "so-called paper architects of the 1970s and '80s ... At that time drawings were indivisible from the disciplinary conception of architecture. These were drawings not of architecture but as architecture."[3]

We can also compare this turn with the shift of the academical pencil hand drawing renderings of classical façades to the speculative collage works of the 1910s avant-garde. Precisely the repeatedly designed and emulated beaux-arts canon during the 19th century justified some of the early modern movement experiments and speculations. As Mario Carpo highlights in his recently published book *Beyond Digital*, these exchanges were broadly paralleled with three ways of making: "hand-making, mechanical machine-making and digital-making ... that of the artisan, that of the factory, and that of computation."[4] Sequential in time, but without obliterating their predecessors, these three technologies are now becoming indistinctly overlapped and we can argue that it is from their creative balance that a critical position towards a sustainable environment could actually be construed. Thus, we can still have a designed goal towards the acuteness of the digital present, and the outcomes of artificial intelligence. More than questioning whether its future is unavoidable, it is urgent to research and unveil fertile exchanges between analogue and digital worlds, ultimately expressing a choice in each potential interchange.[5]

2 Michael Graves, "Architecture and the Lost Art of Drawing," *New York Times* (September 2, 2012): 5. Also available online: https://www.nytimes.com/2012/09/02/opinion/sunday/architecture-and-the-lost-art-of-drawing.html?_r=1&ref=general&src=me&utm_medium=website&utm_source=archdaily.com Graves shows his discontentment: "It has become fashionable in many architectural circles to declare the death of drawing. What has happened to our profession, and our art, to cause the supposed end of our most powerful means of conceptualizing and representing architecture? The computer, of course. With its tremendous ability to organize and present data, the computer is transforming every aspect of how architects work, from sketching their first impressions of an idea to creating complex construction documents for contractors. For centuries, the noun "digit" (from the Latin "digitus") has been defined as "finger," but now its adjectival form, "digital," relates to data."

3 See Sam Jacob, Architecture Enters the Age of Post-Digital Drawing, *Metropolis* (March 21, 2017), https://metropolismag.com/projects/architecture-enters-age-post-digital-drawing. Jacob refers to presentation drawings by Heerlijkheid Hoogvliet (2008), by Office Kersten Geers David Van Severen (2017), but also to the drawings in the master's thesis "Banhos do Tejo: espaços de água e de luz no Aterro da Boavista," by Maria Guerreiro Morais, with which Jacob opened his article. See Maria Guerreiro Morais, "Banhos do Tejo: espaços de água e de luz no Aterro da Boavista" (master's dissertation thesis, Faculdade de Arquitetura da Universidade de Lisboa).

4 Mario Carpo, *Beyond Digital: Design and Automation at the End of Modernity*, (Cambridge, Mass.: The MIT Press, 2023), 3.

5 As Carpo argues, "while the adoption, or rejection, of some new socio-technical models will ultimately be a political choice, the merger of computation and post-industrial automation is no longer a vision for our future: as the climate crisis and the pandemic have shown, this may as well be the only future we have." See Carpo, *Beyond Digital*, 160. At the end, Carpo concludes that actually "nobody knows what post-digital means." Carpo, *Beyond Digital*, 156.

For this choice, a more thorough knowledge of the links between the digital and non-digital phenomena has to be grasped, as Axel Karamercan tells us in the first article published in this issue. In his Heideggerian philosophical point of view, if in terms of our relation to the environment, digital and non-digital activities differ topologically concerning the notions of distance, such as nearness and remoteness, it is also true that a hierarchy cannot be established between both realms, "since there is not an immediate, primary access into the fixed reality of phenomena that provide a set of norms that by which the so-called secondary ones could be distinguished."

In fact, with the concept of "metaenvironment," Miguel Carvalhais underlines how these digital realms "potentially touch and include everyone." But, specifically, regarding design and the use of computational objects, he argues that "a poetic and creative level" is only achieved via "a dialectic process that requires all players to engage in it" and with "tools that are themselves developed as part of the design process itself." This brings an important critique to the shortcomings of an idea of pure automation. Indeed, the criticism on automation has been consistent from the early beginnings of computation. Supervised by Nicholas Negroponte – the leader of the Architecture Machine Group and pioneer of artificial intelligence research in architecture – in 1975 Anne Marie Fourcade interviewed some of the notable early authors in architectural computation and artificial intelligence, and concluded that "the constraint on the production of satisfactory computer aided design systems in architecture is not in the hardware or in the software but in the understanding problem."[6]

Besides the two already mentioned papers published here that respectively open and close a conceptual reading of this issue of JOELHO, the above quote is in tune with the other published articles, which in fact deal with very specific design problems – all in the context of recently finished research projects or which are still under development at different university research labs/centres in São Paulo, Porto, Pennsylvania, Campinas and Barcelona.

Hence, understanding the notions and challenges implied in a specific design tends to be even more crucial when the distance between the places of technological speculation and the contexts of actual application is greater. Indeed, Paulo Fonseca de Campos, Daniella Naomi Yamana and Daniel de Souza Gonçalves present a specific research that proves diverse levels are needed for a successful technological transfer and use of lightweight precast systems, built with digital means. It also shows how their research in the Fab-Lab at FAU–USP starts from previous experiments by João Filgueiras Lima in São Salvador da Bahia, and finds the right balance between laboratorial speculation and implementation. An applied research in outlying areas of São Paulo without any public infrastructures, urges them to "rethink the role of technology in the context of peripheral countries and understand how digital fabrication tools can assist social

6 See A. M. Fourcade, "Architecture and Automatized Methods: Criticisms on the Current Issues," Master in Architecture in Advanced Studies, (Massachusetts Institute of Technology, June 1975), 49. Fourcade interviewed Eric Teicholz, Guy Weinzapfel, Nicholas Negroponte, Aaron Fleisher, Cliff Stewart, Stanford Anderson, Alexander Tzonis, Mlike Gerzso and Timothy Johnson. The quote from Fleisher concerning the shortcomings of automation is poignant: "I cannot think of any device that would automatically change the world and absolutely guarantee a state of grace." See Fourcade, Architecture and Automatized Methods, 49.

processes in solving problems that are largely bound to the territory and the local scale."

Technology per se is thus permanently in need of continuous adaptation and optimization, particularly the challenges intrinsic to fabrication processes and tools. On the one hand, the lab research on robotic hot wire cutting by Pedro Martins and José Pedro Sousa questions how an indirect, subtractive, 3D cutting process can be consistent with "a more socially responsible and sustainable architectural practice" when building with concrete.

Nevertheless, an important message is left at the end, as they also contend that "what is not clear is how such technologies can be critically appropriated in architecture, balancing all these solicitations." On the other hand, for justifying an additive concrete construction technology, the specific features of place are considered key by José Pinto Duarte, Gonçalo Duarte, Nate Brown, Shadi Nazarian, Ali Memari, Sven G. Bilén, and Aleksandra Radlinska. 3D concrete printing is thus explored towards an expedited method for providing affordable housing for indigenous peoples in Nome, a remote permafrost region of Alaska.

Also, the territorial and local scales are witnessing a growing level of acuteness concerning specific, digitally driven methodologies. Marcela Noronha, Robson Canuto da Silva and Gabriela Celani implement city information modelling as a way to render the planning process more participatory from an early design stage. The modelling of the "International Hub for Sustainable Development" in Campinas is taken as the major case study. Participatory decision-making and place-making are balanced in the same process here. This entails one more step concerning an ongoing discussion, from the early 1960s models and their computational implications, on the scales of urban planning and territorial analysis.[7]

Finally, in the context of academic exercises undertaken at the Institute for Advanced Architecture of Catalonia (IAAC) in the framework of the Master in City & Technology (MaCT) – Internet of Cities Studio, Mathilde Marengo, Iacopo Neri and Eduardo Rico-Carranza tutored their students with the aim of testing a methodology in different places in Barcelona, Luxembourg and London that "exploits ecological connectivity, as expression of the implicit and planned tensions between these fragmented landscapes, in order to study, filter, and later validate design decisions."

Hence, we have come to the conclusion that most relevant idea in this issue of JOELHO is the multiplicity of disciplinary approaches that the digital culture has been witnessing in architecture, which depend foremost on "the understanding of the problem." Starting with a restricted group of technophile supporters of the 1990s cyberspace culture, digital environments are now ubiquitous, and also critical when assessing their broader outcomes, architecturally speaking but also socially and politically.[8]

7 We could recall the early efforts at the turn to the 1970s by Negroponte and Leon Groisser at the MIT Urban Systems Laboratory. Negroponte envisioned a kind of a "seeing machine": "… it is possible to build an architectural seeing machine by developing a simple device that will observe simple models. Such a mechanism is the prelude to machines that someday will wander about the city seeing the city. In such a manner, architecture machines could acquire information beyond that which they are given and therefore would have the potential to challenge and to question." Nicholas Negroponte, "Toward a theory of architecture machines," *Journal of Architectural Education*, vol. 23, no. 2 (March, 1969): 12.

8 For a critical review on the political autonomy of digital architecture, see Bruno Gil, "Digital Redux: the confluence of technologies and politics in architecture," *arq: Architectural Research Quarterly*, vol. 19, no.3 (2015): 259–268.

At the end, digital architecture has probably surpassed the prejudice of being an end in itself – to which it highly contributed – and is currently proving its infinite potentialities, at the same time as reckoning with the exponential developments of artificial intelligence. This brings new challenges and added responsibility regarding our response to the demands that the current moment poses to the discipline, a response which takes advantage of the full potential of the digital while maintaining a critical, constructive attitude.

Axel Onur Karamercan
Meudon, France

Inhabiting Digital Worlds

Place, Nearness, Distance

Keywords
— Digital world; topology; place; distance; nearness

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The significance of notions such as digital worlds and spaces remains vague despite their common use in digital humanities, and the extent to which these are bound up with our relation to place and the world is often disregarded. The aim of this article is to clarify the philosophical underpinnings of these concepts, identify the problematic aspects of our relation to digital technologies, and explore the possibility of developing a topological reflection on our being in digital environments. In drawing from the 20th-century German thinker Martin Heidegger's philosophy of place and technology, the article problematizes the modern conception of the world as a mere spatial network and outlines the phenomenological boundaries of digital spaces.
By giving particular attention to explaining the ontological and hermeneutic meaning of the notion of distance, the article elucidates the interplay between nearness and remoteness and arrives at three correlated meanings of distance.

Questioning Digital Worlds: A Reorientation of Place

Digital technologies have been with us for more than half a century. The Digital Revolution, or the Third Industrial Revolution, which resulted in the commercialization of computers, the Internet, digital TVs, and smartphones among many other technologies transformed the very nature of commerce, science, education, media and communication. While recent technological, political, and economic developments suggest that online platforms and activities will increasingly become the norm in the 21st century, the integration of digital tools, applications, and systems into our daily practices by no means guarantees that we are fully experiencing the utter digitization of our world. How digital technologies transform our lives by shifting the boundaries of our dwelling places, redefining the space and place of our interactions with other persons and demarcating the horizon of our everyday practices, remains to be investigated. Addressing the wider implications of the digitization of the world, in a manner that goes beyond technological and entrepreneurial limits and commercial concerns and interests seems necessary and urgent.[1] To be able to answer inquiries such as "*Where* are we when we are situated in and attached to digital spaces?," or "Do we stand at an appropriate distance from the world when engaged digitally?," one must have an understanding of what it means to *be somewhere* and *be connected* to other phenomena (persons, things, places), and certainly, what it means to *be* as such. Accordingly, what I offer in what follows is to elucidate the place-nature of digital technologies.

Although there is a growing literature on the significance of digital and virtual worlds, most contemporary work pays attention to technical dimensions of the matter. Surprisingly, even in most philosophical discussions of cyberspaces, the space and place-character of these platforms are omitted.[2] More attention is given to epistemological and ethical questions, e.g., whether we can know or not we are living in virtual worlds, whether it is wrong to do immoral acts in virtual reality (VR), and cybersecurity. For instance, in his recent book, the Australian philosopher David Chalmers argues that VR is "genuine reality." According to him, we can never know whether we are living in a simulated world or not, which assumes that VR could autonomously exist alongside "reality."[3] The notions of reality and knowledge that are at work in this and similar accounts move within a dualistic Platonist-Cartesian framework that problematically divorces the mind from the body, reality from appearance.

The difficulty of understanding the core issues of digital worlds is due to two reasons. First, as we are so surrounded by digital technologies, we take certain aspects of these technologies for granted. As Iain Thomson puts it, that which seems to be the closest to us, being the most essential and basic, might also be that which escapes our understanding and experience the most easily.[4] Standing too close to phenomena or being completely absorbed in certain situations and activities can make it difficult to make sense of their implicit meanings and implications.

1 A contemporary architect like Patrik Schumacher suggests: "The metaverse is being built as we speak, rapidly. But who is designing it? Who should design it? My thesis is that the design of the metaverse falls within the remit of the discipline of architecture and the wider design disciplines …". https://www.archdaily.com/980196/the-metaverse-as-opportunity-for-architects-an-interview-with-patrik-schumacher

2 The collection of essays edited by Erik Champion addresses this gap in recent scholarship. See: *The Phenomenology of Real and Virtual Places*, ed. Erik Champion (New York and London: Routledge, 2019).

3 See chapter 6, "What is Reality," in David J. Chalmers, *Reality+: Virtual Worlds and the Problems of Philosophy* (New York: W.W. Norton, 2022).

4 Iain Thomson, *Heidegger on Ontotheology: Technology and the Politics of Education* (Cambridge, MA: Cambridge University Press, 2005), 18.

Second, the epistemology-oriented metaphysical tradition considers questions about digital and virtual spaces almost spontaneously to be tied to the meaning of reality. Yet, this implies omitting what determines the realness of the real, namely the more fundamental question of being. A coherent grasp of the topic requires us to reorient ourselves and adjust our focus to reconsider the overall meaning of digital spaces from a more suitable vantage point, which could also allow us to understand, first, our place in the world, and second, how our being placed is to be explored. A topological standpoint, one that can lay out the significance of digital spaces in relation to the human experience of being situated in space, place, and the world, can provide us with that necessary perspective.

Topology and Place

In the history of 20th-century philosophy, phenomenological and hermeneutic thinkers such as Edmund Husserl, Martin Heidegger, Nishida Kitarō, Maurice Merleau-Ponty, Hans-Georg Gadamer, and Kostas Axelos discussed in a myriad of ways that *being situated* in a place, body, or history is the constitutive condition of any experience. Place, or more precisely being placed (situatedness) is exactly that which precedes the "object" and "subject" division since all subjectivity and objectivity must first issue from a particular ground and belong to a certain horizon to be able to be appear as part of a meaningful correlation – a correlation of meaningfulness. As places show us, phenomena, phenomenologists of place, or what one might call topological phenomenologists, are interested in understanding how place determines the specific *appearing* of phenomena.[5]

Among these phenomenological philosophers, Heidegger's thought is probably the most pertinent one for explicitly tying his thinking of being, place, world, and dwelling.[6] His philosophy has been an important source inspiration for important architectural theorists and architects such as Christian Norberg-Schulz, Alvar Aalto, Hans Scharoun, among others.[7] Especially the final phase of Heidegger's philosophy between the mid-1940s and 70s, which he called a "topology of being" (*Topologie des Seins*) is key in that context, as it explicitly focuses on the place (*Topos*, *Ort, Ortschaft*) of the disclosure, or un-concealment (*a-lētheia*) of the meaning of being.[8] If the very appearing – becoming manifest – of the meaning of being can only be possible as an occurrence, the event (*Ereignis*) at issue is the happening of the belonging together of disclosure and hiddenness, which needs the space in *the between* (*das Zwischen*), namely the interval, or the leeway of that becoming apparent. The between is not only the neutral space that connects phenomena, or only a point of passage, but the very possibility of relationality and nearness.[9] Understanding digital technologies requires us to investigate the interplay between appearing and disappearing and explain the tension that exists between situatedness and displacement. Such an analysis can allow us to make sense of the specific kind of relationship between nearness and remoteness, as well as connectedness and distantiation.

5 Luís António Umbelino, "Spaces and Atmospheric Memories," *Joelho: Journal of Architectural Culture,* no. 13 (2022), 16. https://doi.org/10.14195/1647-8681_13_1
6 It must be noted that while my thinking draws a lot from Heidegger's philosophy of place and technology, what follows does not offer a critical analysis or exegetic interpretation of his thought. For such an approach, see Nader El-Bizri's account: Nader El-Bizri, "Phenomenology of Place and Space in our Epoch: Thinking along Heideggerian Pathways," in Champion, *The Phenomenology of Real*, 123–144.
7 Jeff Malpas, *Rethinking Dwelling: Heidegger, Place, Architecture* (London: Bloomsbury, 2021), 2.
8 Martin Heidegger, *Seminare* (Frankfurt: Vittorio Klostermann, 1986), 344.
9 When it comes to the thinking of the between, the works of Nicholas Entrikin, *The Betweenness of Place* (Baltimore: Johns Hopkins University Press, 1991) and William Desmond, *Being and the Between* (Albany: SUNY Press, 1995) come to mind.

In that vein of thinking, thematizing the ontological nature, phenomenological significance, and hermeneutic horizon of the "interval" that originates from digital environments is essential. Philosophical topology allows us to interpret the middle ground at issue by appealing to the *logos/logoi* of the *topos/topoi*: if we go back to the origin of the word *logos*, we find that the root verb *legein* has a wide range of connotations such as laying, gathering, showing, and in that sense of letting-lie-before, "saying."[10] If Jeff Malpas explicitly considers topology to be the "saying of place," this is because thinking topologically implies reflecting on the gathering, saying, laying, and showing of *topos* and how phenomena appear meaningfully to us through the specific situatedness that arises from a specific place.[11] What is crucial regarding the Greek notion of *topos* is that it invokes a sense of boundedness, indeed, a boundedness which is possible only because place is also that which opens to neighbouring sites and locales.[12] As such, a place always has boundaries that make it the particular place that it is, giving access to and connecting with adjacent sites and locations. Here the two other qualities of place, connectedness and particularity, also come to the fore. Namely, not only place is always connected to the world, but it also gathers phenomena which are interrelated, while this specific way of relating to the world distinguishes one place from other places.

Within that context, reflecting on the place-nature of digital worlds concerns, first, hermeneutically, the interpretability of digital worlds from our situated standpoint, second, ontologically, a topology of digital world concerns the *be*-ing of that distance or space that emerges from digital worlds and third, phenomenologically, the significance of the world of manifestation which correlates the builders and the dwellers of digital worlds. Whether our different everyday activities (e.g., communication, socialization, commerce, entertainment) in virtual and digital environments enhance our relation to the world, or the digitization of the world undermines or significantly diminishes the space in which focal activities and practices take place and flourish survive is a central issue. Considering this issue as tied to the place of our inhabitation will help us see whether digital spaces fulfil the four qualities of place –openness, boundedness, connectedness, particularity, and how they challenge the limits or boundaries of place.

The World: The Place of Digitization

As virtual worlds are essentially digital phenomena, it is necessary to turn our attention to the significance of the digital. The prevailing presupposition that needs to be unpacked is that we can understand the digital world(s) without grasping the meaning of the *world*, which is the notion of the world espoused in modern philosophy and science that prioritizes space over place.

A conventional though problematic way of considering digital environments and platforms is to take them as autonomous or independent

10 Heidegger, *Early Greek Thinking*, trans. D.F. Krell and F.A. Capuzzi (New York: Harper & Row, 1975), 60–62.

11 Malpas, *Heidegger's Topology: Being, Place, World* (Cambridge, MA: The MIT Press, 2006), 73–75.

12 In the fourth book of *Physics*, Aristotle defines *topos* as "the first immovable limit of what encompasses the thing". Aristotle, *Physics*, trans. C.D.C Reeve (Cambridge, MA: Cambridge University Press, 2018), 212b, 18–19.

spaces that exist alongside the world, as if they could be seen as parallels or alternatives to it.[13] Part of the problem here is that the concept of world is confusingly employed in the sense of a mere unified totality, as an abstraction of the planet Earth or the globe, and thereby as an indistinct realm that within which things are only contained and bunched together. It would be useful to recall that the concept of the "digital" can be traced back to the Latin word *digitus* (finger) which symbolizes the act of counting by fingers.[14] In that regard, the idea of "digitality" is intrinsically related to the mathematical-geometrical determination of space as calculable and mappable extension, or homogeneous, indistinct territory.[15] Only to the degree that space is organized in a logistic manner, as I will discuss in the next section, can the storage and transfer of physical data, which are the basic principles of computer-based technologies, be possible. Yet, before we organize space by means of computers and establish the numeric arrangement of space, the very idea of "organizing" space itself can be deemed a "digital" endeavour. Willing to transform space into a measurable and exploitable realm for human concerns and projects is at the heart of the Anthropocene, which divorces us our way of being from those of other living beings. Even though as a generation that has gotten used to various debates and discourses on space travel, space tourism and space colonization, observing the notions of "space" and "world" to be attached to the "digital" might not strike us, it must be underlined that conceiving the world and place(s) in such "spatial" terms is rather a modern phenomenon.[16] Even if human practices such as agriculture, architecture, art, among others can certainly be taken to suggest human intervention with and exploitation of "space" – in varying degrees and context – this by no way guarantees that the modern conception of objective space can be readily compared to Plato's *chôra* or Aristotle's *topos*.[17]

In contemporary scholarship, it is already demonstrated that starting from Descartes and Newton, it has become characteristic of modern philosophy and science to view place as a specific point in space as extension.[18] Though here I cannot get into the details of the history of the notions of space and place, I would like to emphasize that what is peculiar regarding the conception of the digital world is that it is often treated as a setting that claims to provide access to the "real" world as if the digital world is situated in another realm or is only indirectly related to the world. What needs to be done first is to designate the specific place of the digital world *within* the world and second indicate the sense in which how the world appears in and through the digital world(s) can also show forth the essence of the digital world. Putting the matter in this way makes it clear that the "virtual" distance between the world and the digital world must become an issue for us.

In what sense does the digital world belong to the world? It can be worthwhile to remember that the most important idea of Heidegger's early thinking is that we cannot think of being – or the question concerning the

13 Malpas, "On the Non-Autonomy of the Virtual," *Convergence* 15, no. 2 (May 2009): 135–139.
14 Ernest Klein, *Klein's Comprehensive Etymology Dictionary of the English Language* (Amsterdam: Elsevier, 1966), 448.
15 Stuart Elden, *Speaking Against Number: Heidegger, Language and the Politics of Calculation* (Edinburgh: Edinburgh University Press, 2006), 3; Hubert L. Dreyfus, *Being-in-the-World: A commentary on Heidegger's Being and Time Division 1* (Cambridge, MA: The MIT Press, 1991), 139.
16 For a discussion of these issues in relation to the spatial idea of the world and place, see: Axel Onur Karamercan, "Could Humans Dwell beyond the Earth? Thinking with Heidegger on Space Colonization and the Topology of Technology", *ISLE: Interdisciplinary Studies in Literature and Environment*, Vol. 92, no. 3 (Fall 2022): 877–902. https://doi.org/10.1093/isle/isaa164
17 Helen Lang's often neglected work on the Aristotelian idea of place includes important insights into the differences between ancient and modern understanding of space and place. Helen S. Lang, *The Order of Nature in Aristotle's Physics: Place and Elements* (Cambridge, MA: Cambridge University Press, 1998), 4.
18 Perhaps the common point of prominent contemporary figures such as Edward Relph, Joseph Fell, Hubert Dreyfus, Edward Casey, Stuart Elden, Robert Mugerauer, David Seamon, Jeff Malpas, Bruce Janz, as diverse as their thoughts are, is that they all point out the significance of the particularity of place and dwelling in distinction from a spatial view of the world. The collected essays edited by Bruce Janz, ed., *Place, Space and Hermeneutics* (New York: Springer, 2018) are one of the richest sources in recent literature that gathers together most of these philosophers and includes discussions of their main ideas.

horizon of the meaning of being – without thinking (as) "being-in-the-world" (*In-der-Welt-Sein*).[19] *What* constitutes the "relationality" of a given setting is not only a spatial sense of connectivity or a multitude of routes that link various points to one another. On the contrary, it is precisely the particular connectedness of the world that constitutes the context or contextualization at issue. The meanings of phenomena are disclosed on the basis of the understanding of being that embodies the meaningfulness of that world. Only because *there is* (*Es gibt*, *il y a*) the world, which is not a mere totality of different "worlds" or phenomena, but rather a place of dwelling and coming-to-presence, the world itself can also appear in (and through) an abundance of ways, e.g., digital, physical, religious, and so forth. However, that does not qualify these manifestations of the world as independent realms or regions. Much rather, each one of these "worlds" *is* a manifestation of the world. This is why it is crucial to recognize that a solely spatial view of the world leads to a mistaken idea of dwelling or inhabitation as mere presence as well as being as a mere biological notion of "life," just as it leads to a misleading view of connectivity and distance for disregarding the nature of connectedness at stake.

But even when we grant that the digital belongs to the world, the nature of this belonging might remain opaque. Consider seeing a world event on the television, listening to a song on the smartphone, participating in a virtual conference, reading a letter in digital format: these are all experiences of distance, that is, either experiences of remote phenomena or distant versions and appearances of these phenomena and events. Here it is crucial to eliminate the quasi-Platonist distinction between the non-digital and the digital in terms of "real" and "unreal," as well as getting rid of the association of the physical with the real and the digital with the false or the replicate. As Chalmers rightfully argues, digital experiences are genuine just like our in-person experiences of phenomena; the song that I am listening to on my smartphone is the "true" song, the virtual conference that I am participating in is the "true" conference, the world event that is on my TV is a "real" event, and so on.[20] However, what should not be mistaken is that if our "real" or "virtual" experience of phenomena in the world are equally genuine, this refers not to the *phenomenal* status of the objects of experience – for what is remote is certainly different from what is near – but rather to their *phenomenological* status as tied to their manifestation to "being-in-the-world." Since distant phenomena or events *appear to be* near while remaining remote, at issue with this "distant nearness" is considered to be some sort of an ontological "as if" effect. However, considering digital spaces as a mere replacement of physical phenomena assumes that on the one hand there are "real" entities and on the other there are their digital equivalents. Such a way of conceptualizing the link between digital and non-digital phenomena not only fails in making sense of digital entities and platforms as *true* manifestations of the world on their own, but it also blurs our understanding of non-digital phenomena as non-mediated, immediately accessible stuff.

19 Malpas, *Heidegger's Topology*, 73–75.
20 Chalmers, *Reality+*, 113–114.

21 Thomas Sheehan, *Making Sense of Heidegger: A Paradigm Shift* (London and New York: Rowman & Littlefield, 2015), 73, 106, 121.
22 Heidegger, *On the Way to Language*, trans. P. Hertz (New York: Harper Row, 1971), 103.

Phenomenology teaches us that the meaning of things in the world are always *understood* through certain meaning-structures, conditions, and moods. This does not concern the presence of phenomena, but their meaningful presencing. Hence, phenomenology is a unified study of correlations:[21] it studies the threefold correlation between the meaning of phenomena, the sources of the meaning of phenomena, and the nature or the structure of that correlation. To be sure, perceiving phenomena in "real time," in their "physical" presence, is also a particular experience – a product of a certain source of meaning on its own. That is to say, the digital and the "really real" are not readily comparable in terms of their proximity to reality. Whether giving a "in-person" or "online" seminar, we are not provided with a set of epistemological norms to judge if our practical involvement is real or not. We are simply immersed in the world, captivated in the act of speaking to the audience.

If we are always already encompassed within the world of experience, the epistemological status of digital experiences as true or not does not play a role in our sense-making processes regarding the authenticity of those experiences for they continue to shape our being in the world. While digital and non-digital activities do differ in terms of our relation to environment, and they certainly can be compared in terms of how our experience of space and place vary; there can be no experiential hierarchy between the digital and the non-digital since there is not an immediate, primary access into the fixed reality of phenomena that provide a set of norms that by which the so-called secondary ones could be distinguished. As the conditions and correlations of experience are unrepeatable and irreversible, particularity, singularity, and one-timeness determines the very nature of experience itself. Put more concisely, the bodily experience of phenomena can be as "artificial" or "remote" as their digital equivalents, if the person at issue is not fully immersed in her or his involvement with(in) the world. Having clarified how not to think the place-nature of digital spaces and how not to divorce them from the world, let us turn to the central problem, which is to specify the kinds of distance that occur from the digital world.

The Logistics of Distance

First, let us consider Heidegger's suggestion regarding the nature of distance in his later thought:

> Two isolated farmsteads – if any such are left – separated by an hour's walk across the fields can be the best of neighbours, while two townhouses, facing each other across the street or even sharing a common wall, know no neighbourhood.[22]

This thought, which clearly distinguishes the qualitative aspect of distance from the quantitative, shows to what extent the link between place, dwelling, connectedness, and distance has important implications for understanding our dwelling in digital worlds. The following passage from his 1950 lecture "The Thing" is an extremely relevant example as to how clearly Heidegger identified the issues relating to digital culture in advance:[23]

> *All distances in time and space are shrinking.* Man now reaches overnight, by plane, places which formerly took weeks and months of travel. He now receives instant information, by radio, of events which he formerly learned about only years later, if at all. The germination and growth of plants, which remained hidden throughout the seasons, is now exhibited publicly in a minute, on film. Distant sites of the most ancient cultures are shown on film as if they stood this very moment amidst today's street traffic. Moreover, the film attests to what it shows by presenting also the camera and its operators at work. The peak of this abolition of every possibility of remoteness is reached by television, which will soon pervade and dominate the whole machinery of communication.[24]

While it may appear as if Heidegger is criticizing our use of the technological devices mentioned in the passage, this would be a simplistic interpretation. Crafting and using technical objects is clearly an essential part of our being.[25] The aim of Heidegger's critique of technology is not to replace digital *technē* with preindustrial tools and instruments, but rather to urge us to try to understand its particular *logos*, i.e., what it shows about our interaction with the world which no longer signifies a simple means-ends relationship.[26]

In a nutshell, the danger that occurs from our interaction with digital technologies is the pursuit of complete overcoming of space and time, which implies a distanceless relation to phenomena. Such distancelessness, which for Heidegger brings no nearness but only its annihilation, disregards the ontological happening and disclosure of place and focuses primarily on establishing immediately connectable points on a spatial plane with no boundaries. If the manifestation of phenomena requires the space in and through which they can appear, the abolition of distance implicates the end of any appearing and relationality. In rendering phenomena as readily displayable and exchangeable data between online users and consumers, digitization conceives of space and time as *obstacles*. This yields a completely unique experience of the world, for instance, compared to Kant's modern subject who considers space and time as the *conditions* of the possibility of experience. If Kant's space and time, as the forms of intuition are restrictive conditions of experience, thus, culturally what could be considered products of a "conservative" modernity, the so-called post-modern, "liberal" response to it is a transgressive one. The digital experience of space and time challenges the boundaries and the nature of the "between" at issue in a way that it tolerates no more boundaries. Yet, a more appropriate relation to place and distance stands right in the between and beyond. In order to

23 Idem., *Vorträge und Aufsätze* (Frankfurt am Main: Vittorio Klostermann, 2000), 165–188.

24 Idem., *Poetry Language Thought*, trans. A. Hofstadter (New York: Harper Collins, 2001), 163.

25 Idem., *The Question Concerning Technology and Other Essays*, trans. W. Lovitt (New York and London: Garland Publishing, 1977), 4–5.

26 The essence of modern technology, *Gestell*, which is translated by commentators with different terms such as "framework", "enframing", "positionality", "inventory" – implies that our thinking runs the risk of turning into a merely calculative mode of arranging, organizing, and stocking that no longer allows phenomena to emerge and grow as things with which we can engage meaningfully. While the exploitation and optimization of phenomena become our sole way of experiencing *technē*, we ourselves turn into instrumental objects of technology.

preserve a safe space in which we can interact with digital technologies rather than being completely overwhelmed by them, we must distinguish the dynamic space – the interval – that occurs from, belongs to, and constitutes the relationality between phenomena and the absolute space as an area within which phenomena are placed as commodities.

What is so easy to miss regarding the digital world is that insofar as the tools, objects, designs, software and interfaces of digitization hinge on a global network that connects physically distant "subjects" and/or "objects," they are also reliant on physical distance and a sense of situatedness. Without distant dwellers who are placed in separate locations and contexts – therefore without the physical distance between them – a digital or any kind of "connection" would not be needed either. Nonetheless, internet technologies turn distance into a matter of speed, and more precisely, speed of connection. How long it takes for an image, video, text, or a document to be sent and to *appear* on another screen, while preserving their "real appearance," seems to define the ambitions of current day information technologies. The danger at issue here is that the delivery of persons, news, things from point A to point B in the shortest time possible defines our primary and the sole idea of connectivity and distance, this would gradually lead to the marginalization and even complete disappearance of the experience of the crossing of the between, the "interval," which would also imply the complete absence of experience – complete disappearance of a sense of space, time and place.

It is not surprising that the more consumers of digital technologies are driven further away from one another as isolated subjects, which is one of the characteristic features of a sense individualism that feeds from the modern, Cartesian idea of self, the more they will demand these technologies in order to be "connected." For instance, it remains questionable whether metaverses, which is a term originally coined by Neal Stephenson in his 1992 book *Snow Crash*, today described as "a future Internet of persistent, shared, 3D virtual spaces," can provide the social connection, immersivity, and work efficiency that they promise.[27] Is it rather that the connectedness, immersivity and efficiency that metaverses seek to provide can only exist in and be based upon a world of social disconnection, practical detachment, and procrastination, owing to the very technological way of being from which they originate? Let us underline: if the digital world leads to the disappearance of nearness, this is not because we live away from other persons and wish to remain in connection with them despite that distance, but because the only meaning of connection becomes "remote connection." This is precisely why Heidegger writes, as cited above, "*all distances in space and time are shrinking*." Instead of letting distance remain *as* distance, digital technologies are capable of transforming it into a "distant nearness," namely, distance itself experienced *as* nearness, or nearness that is only found in distance. However, the happening of nearness, in the sense of "becoming and remaining near," depends on the preservation of distance

27 Patrice Flichy, "The Social Imaginary of Virtual Worlds," in *The Oxford Handbook of Virtuality,* ed. Mark Grimshaw, (Oxford: Oxford University Press, 2013), 702.

and the two cannot be treated separately. Therefore, it is key to question whether digital technologies can identify an *ethos* that does not treat the boundaries and the ways of the world as mere routes of information transportation. In other words, is it possible to construe a non-metaphysical relation to digital worlds and spaces that can bring nearness?

As also recently examined by Anna Kouppanou, it is possible to consider the experiential kinesis of digital phenomena as part of the problem of "metaphoricity."[28] The Greek word "metaphor," which is composed of the prefix *meta,* meaning "beyond, away" and the verb *pherein*, meaning "bringing, carrying," precisely implies the relocation of phenomena from one place to another.[29] While it is no secret that Heidegger thought that a symptomatic feature of meta-physics is to think of being in terms of metaphors, insisting that his famous idea of language as the "house of being" must be conceived of neither as a metaphor nor a sole transfer of poetic imagery, the notion can also be considered in the sense of the event or the interplay of nearness and distance.[30] Although, as Kouppanou underscores, Aristotle originally considers metaphors the "improper transposition of names," Heidegger takes the metaphorical thinking of being and dwelling to be an improper interpretation of our situatedness in the world.[31] This gives rise to a misleading idea of nature (*physis*) as a biosphere "objectively" distantiated from the world of human "subjects," since *physis* rather indicates the emergence, growth of being(s). As such, the ideal would be to render digital technologies attuned to *physis* rather than transforming nature into a space of human wills and procedures, the Nietzschean "will to power," or even to that of "will to will." In that sense, the task is to find out how we could say yes to digital technologies without letting our dwelling to turn into a mere mechanism of remote programming and representation.

Kouppanou's suggestion is to read the transposition that stems from the digitization of the world not only negatively, not as a displacement that automatically defines phenomena as distant, technical, artificial, non-sensible entities, but as a new mode of disclosure, giving way to *poietic* (more on this shortly) revelations of being and dwelling. The most important aspect of Kouppanou's argument, therefore, is to distinguish utter digitization of all phenomena from the possibilities of revelation that the digital dimension of *technē* offers. Put more explicitly, the goal is separate the overpowering essence of digital technologies that transform all relations into distant relations from the human being's capacity of illuminating the world through emerging digital crafts.

Even if "overcoming" distances is nothing new for us considering our anthropological history, how this "overcoming" is achieved is what matters the most. To take distance from Heidegger, it is possible to argue that most of our linguistic and cognitive skills such as communication, imagination, and storytelling are abilities that allow us to "displace" ourselves from our physical environments. Ideas of telepathy, time travel, or teleportation, as also widely issued in works of science-fiction literature,

28 Anna Kouppanou, *Technologies of Being in Martin Heidegger: Nearness, Metaphor and the Question of Education in Digital Times,* (New York: Routledge, 2018), 113.

29 It is interesting to consider that the modern Greek word *metaphora* literally means "transportation" as tied to the logistics of goods.

30 Heidegger, *Pathmarks,* ed. William McNeill (Cambridge, MA: Cambridge University Press, 1998), 272.

31 Kouppanou, *Technologies of Being in Martin Heidegger*, 41.

have long been part of our popular cultures. We could say that the entire history of human existence is also a history of the disappearance of physical distances owing to the constant invention of new technologies. In fact, is not language the very first medium that by which we learned to "overcome" mental and physical remoteness? For instance, words are not the things themselves but their "signs": they refer us to the things, which indicates the necessary *interval* between them. Reading a novel or listening to a story is already an immersive experience, allowing us to imagine ourselves in other places, historical epochs, settings and contexts. It could be said that technological devices such as radios, televisions, cameras, satellites, telescopes do the same: they are instruments that are designed to receive, transmit, and show that which is remote in space or invisible from our immediate perspectives. Withdrawing ourselves from our immediate environment by some media, whether that is technological devices or tools of our intelligence, and at the same time physically remaining within our environment, constitutes our very being. However, we must highlight the fundamental difference at stake: if our mental capacities grant us the possibility of "seeing" things, bringing events, persons, phenomena near in our imagination, technological devices claim to achieve the same "manifestation" on an "objective" level. It is this claim of objectivity that transforms the world into a "world picture" that can be captured in its "real" being.[32]

Based on what I have discussed so far, it becomes possible to define three kinds of distance which are strictly interrelated: (1) *physical distance* is the one that exists between places, persons, events, and phenomena. Physics translates this space in the between into a quantifiable sort of distance and calculates it by using mathematics. Conceiving of distance as only something to be measured by numbers leads to the metaphysical conception of the world, space, nearness, and connectivity; (2) *metaphysical distance* is that which emerges from the attempt to overcome the physical distance in its totality by means of digital technologies. In other words, metaphysical distance appears as a result of the denial of distance and the finite nature of place. It is based on a logistic idea of space, and the metaphoricity in which it is involved implies an infinite transfer of phenomena that remains in constant displacement. Now what is being measured is not only the distance itself, but also the overcoming of that distance; (3) *meta-metaphysical,* or *poietical distance* is that which emerges from the need to appropriate the metaphysical relation to space and distance. Hermeneutically appearing as a possibility and ontologically appearing as a necessity, poietical distance is the source of any distance as such, which occurs from our phenomenological situation of being bounded by place and being connected/open to other persons and places. Poietical distance is "meta-metaphysical" not because it is "beyond" the metaphysical, but rather because digital spaces reveal the possibility of problematizing the nature of place in a new way, as they show forth the

32 Heidegger, *Off the Beaten Track*, trans. J. Young and K. Haynes (Cambridge, MA: Cambridge University Press, 2002), 67.

33 As regards with the link between architecture and digitality, Malpas draws on the topic of “parametric design” which, put in a nutshell, concerns the tension between computer-based and place-based design. Malpas, *Rethinking Dwelling*, 135–144.

34 Heidegger, *Poetry Language Thought*, 157.

ever-present interval; the space of relationality that always exists between the self and the world, which remains implicit and oblivious to metaphysics. In other words, poietical distance is capable of displacing the logistic displacement of metaphysics. At issue, thus, is not a teleological hierarchy between the three definitions of distance; it is simply that the poietical distance allows the physical and metaphysical to appear as such.

Consider the following: visiting a museum from distance obliges us to see that in visiting the museum remotely, we find ourselves not only remote from the historic world in and through which the works of art at issue are withdrawn and uprooted, but we also stand in distance from the city, the street, the museum building, the gallery, in short, the entire artistic and urban context that embodies the primary displacement of the works of art. The secondary displacement of the work of art can awaken us to inquire into the nature of the primary displacement and problematize the topological meaning of museum. In that sense, experiencing poietical distance requires a specific attitude vis-à-vis place and the world, where instead of attempting to eradicate physical distance, the builders and the dwellers of the digital world(s) make sense of digital experiences not as replicates that replace the physical experience. By turning the metaphysical distance on its head, the digital experience of the world can be taken to constitute its own and unique manifestation of the world. This provides the leeway for taking a step back from “overcoming.” In that regard, the trifold idea of distance naturally relates to the question of the link between digitality and dwelling, which also has important implications for architecture.[33]

Builders and Dwellers of Digital Worlds

In our era of global warming and environmental catastrophes, we see more and more clearly how the design and planning of our houses, streets, cities, urban areas, and natural environment fundamentally determine the ways in which we experience the world. Today we are desperately in need of cities and urban areas that can breathe, lacking the necessary space and openness. The same can be thought with regards to the building of digital environments and existing digital platforms. One of the crucial dimensions of the subject is the relationship between the builders and the dwellers of digital spaces. In his famous 1951 essay “Building Thinking Dwelling” (*Wohnen Denken Bauen*), Heidegger points out the link between building and dwelling by saying:

> The nature of building is letting dwell. Building accomplishes its nature in the raising of locations by the joining of their spaces. *Only if we are capable of dwelling, only then can we build.*[34]

Dwelling, or inhabiting the world, is our *way of being*. Accordingly, different ways of building (*bauen*) would allow different kinds of dwelling (*wohnen*) to emerge. Insofar as building and dwelling belong together, the underlying

35 Klein, *Klein's Comprehensive Etymology Dictionary*, 101.
36 Heidegger, *The Question Concerning Technology*, 10.
37 Idem., *Poetry Language Thought*, 219.

principles of the construction of digital spaces and places matter to us as their dwellers, which also relates to the core matter of architecture.

Firstly, it would be useful to consider that in ancient Greek, the word architecture originally stems from the word *architekton*, literally meaning master, chief builder (*archon* + *tekton*).[35] Here it is equally important to remember that *tekton* is related to *technē,* commonly interpreted as "art" or "craft," but thought more essentially, it implies a sense of "bringing forth." It could be said that architecture brings out the essence of our existing relationship with space, place, and the world. Thus, before being a *technē*, the essence of architectural "bringing forth" is poietic.[36] One question that arises here is the link between the architectural and the poietic. To understand that connection, a more complete understanding of the poietic is necessary.

The origin of poetry and the poetic is *poiesis*, which in Greek essentially is related to "making" (*poieō*) and has great importance for Heidegger's thought of place and dwelling. Heidegger's main point is that the "making" of *poiesis* must not be confused with the mere production or creation of things. Production of a new phenomenon first necessitates openness and space; it demands the clearing within which it can be imagined and built. Thus, at first, making appears as a heedfulness of space, letting the place of a phenomenon disclose itself as such. Heidegger conceives of the making of poietic as the "measure-taking" of the between, which is also where building and dwelling occurs between the earth and the sky. Only by appropriately measuring the space of the between, the interval, one can reveal the hiddenness of what is hidden and disclose the being of a thing in harmony with its particular way of being present.[37] The measuring at issue thus is not quantitative calculation, but the meditative experience of the dimension of disclosure. Master builders and dwellers are *poets* – those who build and dwell po(i)etically.

Considering the metaphysical distance that emerges from digital spaces, can we say that these environments bring forth the necessary room for us to be able to inhabit the world in a poietic way? At first, it seems that the very word "inhabiting" itself would contradict the possibility of inhabiting the world from distance since inhabiting a place precisely implies being situated *in* a habitat or a dwelling-place. But as I have attempted to show, we must be careful not to take inhabitation as mere physical being-in or being-near since doing so leads to another problematic position, only to treat place as a "restrictive" phenomenon. Indeed, being *somewhere* always implies not being elsewhere. However, one also needs to grant that precisely because it is possible for us to experience distance *as* distance that we have been able to invent technologies that permit us to engage with different, previously unintelligible appearances of the world and phenomena. This is the reason that the so-called "restrictive" essence of place is in fact also its "freeing" dimension, which requires us to assess distance as an inherent element of our experience of place and being in the world, an interval which opens us up to the world. In turn, the effort to "free" us from place is exactly the source of the problematic metaphysical relation to place, as well as identity and culture.

Even if there can be no nearness without the interval – the betweenness – of distance, such an experienceless world, one that immediately appears before our eyes in its absolute reality, seems to be the goal of most tech companies, states, and state-funded agencies. In the same vein, the existing paradigm of the virtualization and simulations of space, place(s), historic and existing sites remains a representational one, where the aim is to represent places by remaining faithful to what *is* or *was* in those places, that is, by appealing to verisimilitude.[38] Yet, still, could it be possible to simulate the experience of dwelling in its entirety by digital techniques? Perhaps, a more complete answer to this question exceeds the limits of a purely philosophical inquiry and needs to be investigated in an interdisciplinary manner that involves philosophers, architects, web designers and informaticians.

An initial way of testing this idea, especially in a way that is of interest to all of us as researchers, lecturers, and students in our academic world would be by producing a prototype of an architectural virtualization of a campus site or some of its buildings. Such a virtual production could help us compare a university-dweller's experience of being in the campus site with those of a distant student's and a tourist's respective virtual, online visits. The hypothesis of such a creation would be to see how the distant student experiences the *physical distance*, how the tourist experiences the *metaphysical distance*, and how the university dweller experiences the *poietical distance*. This could help us see what could be captured about the finite nature of dwelling in a comparative manner and tell us more about the links between embodiment and culture, as well as the methodological possibilities of bringing philosophy, architecture, and information technologies together in a way that they could work towards overcoming the metaphysical – representational – applications of virtualization.[39] Today, learning to take a step back from metaphysical objectification of place and the world seems to be the only therapeutic approach to digital spaces in order to benefit more from them as a new disclosure of the world.

Thinking on place with Heidegger shows that, just as web designing is fundamentally an architectural enterprise, so the practice of architecture is fundamentally poietic. Whether we will be able to keep these disciplines connected, and not only in an academic way, but in the actual taking place of building, designing, and thinking, will define the nature of our dwelling in the 21st century. What is needed to that end is to identify the ways in which physical, metaphysical, and poietic manifestations of distance relate to another without letting the metaphysical to get in the way of the poietical. In turn, this implies neither overestimating the nearness of the physical nor trivializing the remoteness of the digital, but letting the poietical be the measure of building and dwelling.

38 Janz, "Virtual Place and Virtualized *Place*" in *The Phenomenology of Real and Virtual Places*, 61.

39 For carrying out such a work, the University of Coimbra's UNESCO world heritage site Alta and Sofia campus, which offers an important historical, architectural, and urban setting, would be an ideal candidate. In that regard, Erik Champion's approach, which highlights how the architectural not only has to do with nature and the ontological, but also with culture and the bodily dimension of dwelling, is key. Champion, "Norberg-Schulz: Culture, Presence, and a Sense of Virtual Place," in *The Phenomenology of Real and Virtual Places*, 151.

Paulo Fonseca de Campos
Faculty of Architecture and
Urbanism at University of São Paulo

Daniella Naomi Yamana
Faculty of Architecture and
Urbanism at University of São Paulo

Daniel de Souza Gonçalves
Faculty of Architecture and
Urbanism at University of São Paulo

Resilient Society, Resilient Design

Digital Fabrication Technologies and the Concept of Place

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Big cities in developing countries face many obstacles related to the built environment when confronted by socio-economic inequalities, which is reflected in the uneven access to basic living infrastructure, such as sanitation and housing. In the light of new approaches to traditional materials and building techniques, the aim of this article is to investigate the use of digital fabrication tools in the production of lightweight precast systems for the social production of habitat in Brazil.

To develop a clear assessment of the possibilities created by these technological alternatives, two academic applied researches are considered as case studies: a modular sidewalk for rain water drainage and a precast building system for housing. The main goal here is to discuss the role of high-tech solutions — such as digital fabrication tools and lightweight precast systems — in promoting urban, community-driven, upgrading initiatives in precarious settlements, accompanied by local economic development.

Introduction

The application of design on an urban scale is of growing importance in environments in an increasingly connected world, where city production takes place amidst complex social, local and at the same time global relationships, offering project opportunities of great relevance. Faced with sophisticated production and consumption relations that take place in the contemporary city, the city itself has become a place of high sociocultural power and intensity and demands design solutions capable of establishing and strengthening bonds of belonging and identity between the inhabitants and the places they occupy in different urban contexts.

The reflection proposed here is based on the implementation of urban intervention projects aimed at improving the social habitat in cities like São Paulo, involving the following key ideas:

The use of digital manufacturing as a disruptive technology, not only from the point of view of its innovative technical possibilities, but, above all, in terms of fostering new social dynamics of production and consumption.

The use of ferrocement or high-performance micro concrete as a technological alternative to develop the lightweight prefabrication and new fields of application, particularly aimed at urban infrastructure and social housing.

The employment of industrialised architecture as a technological alternative for the development of solutions particularly focused on infrastructure and urban habitat.

The applicability of technologies developed within the research project "Resilient Society, Resilient Design" that has been promoted for nearly six years at FAU–USP (Faculty of Architecture and Urbanism at University of São Paulo), through its territorialization in local contexts and on local scales, according to a vision that brings these processes to concepts involving participatory practices in design, such as co-creation and co-governance.

The promotion of physical interventions accompanied by local socio-economic development, promoting, whenever possible, a popular and solidarity economy through technology transfer and collective entrepreneurship.

In this last vector, in particular, one can even refer back to the existing tradition of the social production of habitat in Brazil and Latin America, where the user acquires the status of protagonist and design agent in participatory processes.

In a recent series of articles by Nikos Salingaros et al., the authors propose a reflection based on a system of good practices for social housing, grounded on experience and suitable for general situations.[1] To this end, examples of housing solutions appropriate to the Latin American context and aimed at long-term sustainability are presented in order to lead residents to take root in their built environment. The authors refer in

1 Nikos Salingaros et al., "Socially-Organized Housing: Design That Establishes Emotional Ownership," *Archdaily* (March 2019), https://www.archdaily.com/913586/socially-organized-housing-design-that-establishes-emotional-ownership (accessed in 12/05/2022).

particular to the work of Christopher Alexander, highlighting participation as a basic principle.[2]

In his long career as an architect and urban planner, Christopher Alexander was commissioned to plan and build social housing for various governments. Often, opposing the design requirements established by the government agency that had hired him, Alexander insisted on user participation as the only way to produce built forms that were "loved" by their occupants.[3] In his projects, it was essential to involve future residents while planning their living space, the configuration of accesses and common areas, which did not always please the authorities, who feared seriously weakening their control over urban guidelines.

Contextualization

According to a survey carried out by the National Sanitation Information System, only 52.4% of the Brazilian population is served by sewage collection systems, meaning that 100 million Brazilians do not have access to this service.[4] This data is only a sample of what constitutes housing typologies in areas occupied by low-income populations, more specifically, slums. In Brazil, those are, as a rule, extremely unfavourable, constituting dramatic living situations, taking into account poor sanitation conditions, water and soil contamination, epidemics, landslides and floods.

Therefore, when introducing the theme of technology in the construction of social habitat, it is necessary to clarify the difficulties that a country like Brazil has in this area and the consequent need for effective basic sanitation policies. Faced with the government's inability to offer appropriate solutions, relying solely on conservative management and building methods to intervene in precarious settlements, it is of vital importance to think about alternatives that promote improvements in quality of life for these vulnerable groups.

Within this context, the objective here is to investigate the use of technological alternatives in the improvement and reordering of irregular settlements and seek a better adapted approach to the demands of a given territory. To this end, the "Resilient Society, Resilient Design" research project developed by DIGI-FAB research group (digital fabrication technologies applied to contemporary production of design and architecture) from FAU–USP is presented, exemplifying the use of digital manufacturing processes in the production of high-performance ferrocement building components for housing and infrastructure.

This paper, rather than simply narrating ongoing experiences or describing technologies that can be transferred and used in the construction of social habitat, has as its main concern the discussion of ways in which a guarantee of healthy and dignified living conditions can be granted to marginalised communities considering, however, the need for rationalisation of public resources allocated to social housing and basic infrastructure.

2 Ibid.
3 Christopher Alexander, *The Nature of Order: Books One to Four* (Berkeley, CA: Center for Environmental Structure, 2001-2005), quoted in Salingaros, "Socially-Organized Housing."
4 SNIS—National Sanitation Information System, *Diagnóstico dos Serviços de Água e Esgotos – 2017 [Diagnosis of water and sewage services – 2017]* (Brasília: Ministério do Desenvolvimento Regional, 2019), 27.

Digital Fabrication Technologies

As already mentioned, this paper addresses an applied research dedicated to developing building systems for urban interventions, specifically in precarious urban settlements located in the lowlands or floodable areas. For this purpose, it is focused on developing lightweight prefabricated components made with high-performance ferrocement and moulded in formwork produced with the aid of digital manufacturing, designed for infrastructure (sanitation and rainwater drainage) and social housing building elements. As the research deals with areas of economic and social vulnerability, another main purpose of this research is to promote urban improvements alongside economic development, through popular economy ideals such as self-management and community production.

Nowadays, the term digital fabrication encompasses different manufacturing processes that use computer numerical control (CNC) equipment or machines, which can be classified as additive, subtractive or conformative. Additive manufacturing processes, commonly known as 3D printing, occur with layer-by-layer deposition of a base material, which can be liquid, solid or powder. In subtractive processes, the final object is obtained by removing parts of a base material, in laser cutting or milling machines. Lastly, in manufacturing by conformation methods, the base material is mechanically deformed.

Regardless of which process was chosen, the logic behind digital fabrication remains the same: a virtual model is generated by computer (CAD—computer aided design) into which are introduced the parameters pertinent to its manufacturing (CAM—computer aided manufacturing). Then, the program generates a sequence of numerical instructions, named G-code, which commands the computer-controlled equipment (CNC) so that it performs all the tasks necessary to fabricate a given object.[5]

In other words, digital fabrication logic follows a file-to-factory concept, where designs are developed on digital platforms and executed with the aid of CNC machines. The fluidity of this production cycle is possible due to integrated CAD and CAM software, making design and production inseparable within the process. Also, in contrast to machines used in mass production lines, CNC machines are dimensionless and reprogrammable, allowing flexibilization of manufacturing operations. Custom objects can be produced from one to very few units without cost increase, which enables mass customization.

Since the early 1990s, architects have been testing digital fabrication limits in the field of civil construction, seeking to explore complex geometries that would be extremely hard to produce by conventional methods. However, the use of digital manufacturing processes seems to be restricted to monumental buildings, when there are no cost limits, like Olympic stadiums, museums or corporate headquarters. This trend might indicate that digital technologies are not yet available outside the restricted niche of high-tech architecture.[6]

5 Paulo Eduardo Fonseca de Campos and Eduardo Ignacio Lopes, “A fabricação digital aplicada à construção industrializada: estado da arte e perspectivas de desenvolvimento” [Digital manufacturing applied to industrialised construction: state-of-the-art and development perspectives], *Revista Concreto & Construção*, no. 85 (January/March 2017): 22–29.

6 Márcio Minto Fabricio, “Industrialização das construções: revisão e atualização de conceitos” [Industrialization of construction: revision and updating of concepts], *Revista do Programa de Pós-Graduação em Arquitetura e Urbanismo da* FAUUSP, no. 20 (June 2013): 228–248.

7 Campos and Lopes, “A fabricação digital.”
8 João Filgueiras Lima [Lelé], “Technique without giving up beauty: notes on being an architect,” accessed May 27, 2022, https://www.vitruvius.com.br/revistas/read/entrevista/18.073/6891?page=2
9 Ibid.
10 Ana Gabriella Lima Guimarães, “A obra de João Filgueiras Lima no contexto da cultura arquitetônica contemporânea [The work of João Filgueiras Lima in the context of contemporary architectural culture]” (PhD thesis, FAU–USP, 2010).

Ferrocement Technology and Lightweight Precast Systems

Since the 1980s in Brazil and Latin America, it has been possible to observe a trend towards the development of increasingly lighter building systems and components, providing greater technological density to these products and guidelines for a promising future in the precast concrete segment.

This became possible as parameters were established for the application of the so-called “high-performance concrete” in this area of civil construction, particularly during the 1990s, with the aim of increasing the diversification of products offered to the industrial, commercial and housing markets, an important factor to gain competitiveness for the sector.[7]

When it comes specifically to the evolution of lightweight prefabrication in concrete in Brazil, it is necessary to recognize the fundamental role played by João Filgueiras Lima, known by the nickname Lelé, a modernist architect with a large collection of projects using this building technology.

Since the beginning of his work as an architect in the 1950s, Lelé has developed unique experiences using prefabrication in architecture production. In an interview with the Brazilian architecture website Vitruvius, when asked about his vision about traditional construction processes, Lelé highlighted his intention to produce prefabricated parts using affordable technologies, so populations with specific demands could, assisted by a professional architect, be protagonists in the production process.[8]

> What we argue is precisely the dissemination of a building system that would almost allow self-construction. It’s like Lego that we assemble from these components, in a simple way, that could be learned by a low qualified workforce, and fast.[9]

From this thought, in 1979 Lelé developed projects for lightweight prefabricated systems for infrastructure, in slum urbanisation interventions in the city of Salvador, Bahia, promoted by RENURB – *Companhia de Renovação Urbana de Salvador* (Salvador Urban Renovation Company).[10]

The flood drainage project (Figure 1) used ferrocement as material to create lightweight prefabricated thin-wall and high-strength elements. Lelé gives a good definition of the technique when asked about its extensive use over the years of his production:

> Ferrocement is nothing new; it was explored, and very well handled, by the French engineer Joseph-Louis Lambot two hundred years ago. There are even experiments made with boats at that time. In the French Construction Museum there is such

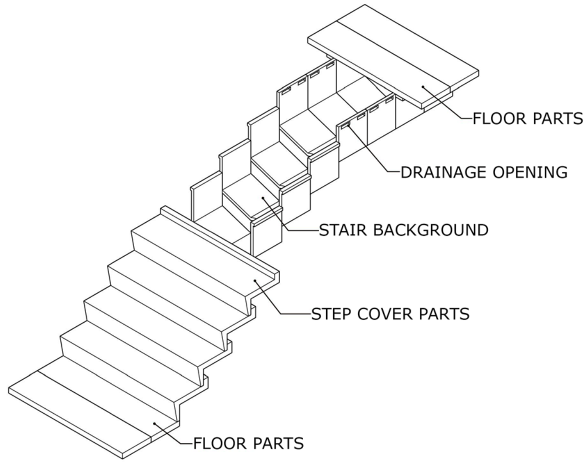


Fig. 1 João Filgueiras Lima (Lelé), Lelé's flood drainage design in RENURB, Salvador, 1980 (J.F. Lima).[11]

> equipment that was rescued from the bottom of a lake, and that perfectly expresses all the technical quality of the material. In the 1940s, Pier Luigi Nervi used ferrocement, which he called 'ferrocemento.' There are some nuances between this product, which was explored by Lambot, then by Nervi, and what we practice now. In fact, in these two experiments, the ferrocement had a much higher steel reinforcement content than what we use today, even as a matter of cost.[12]

Ferrocement or reinforced mortar, as defined by Lelé, represented a major technological advance in the production of precast elements, even though it was a partially artisanal technique. Lelé's experiences resulted in an increase in the quality of the works with popular participation, monitoring of the project and execution. The transitional schools in Abadiânia (Goiás), developed in 1982, are examples of projects in which popular participation and training of local labour were fundamental for the quality of the project. Metal moulds were used for the production of ferrocement elements, exquisitely dispensing with the use of any specific machinery for displacement and assembly.[13] The result of this experience was the construction of local schools by the population's own hands, which, now trained and aware of the process, can replicate it in new actions for local demands.

In addition to these early experiences, in the 1990s Lelé also developed large-scale projects with prefabricated systems (Figures 2), mainly in his work at the Technology Centre of the SARAH Network (CTRS),

11 Guimarães, "A obra de João Filgueiras Lima."
12 Lelé, "Technique without giving up beauty."
13 Cristina Câncio Trigo, "Pré-fabricados em argamassa armada: material, técnica e desenho de componentes desenvolvidos por Lelé" (Masters thesis, FAU-USP, 2009).

14 Trigo, "Pré-fabricados em argamassa armada."
15 Campos and Lopes, "A fabricação digital."
16 Ibid.
17 SARAH Rehabilitation Hospitals Network, "Conheça a Rede SARAH de Hospitais de Reabilitação" [Discover the SARAH Network of Rehabilitation Hospitals], SARAH Network, accessed May 2022, https://www.sarah.br/a-rede-SARAH/nossas-unidades/

where he explored prefabrication with more resources for the construction and maintenance of the SARAH Rehabilitation Hospitals Network.[14] In this way, Lelé's production was marked by the development of new prefabrication technologies, which was presented through his projects as a response to the most diverse social demands.

Ferrocement or reinforced mortar has technological foundations developed in Brazil over six decades that enabled it to become a high-performance micro concrete in the last 20 years—either because of its properties of high mechanical resistance to compression and low porosity, or because of the economic possibilities for its application.[15] They are based on the initial experiences with the "ferrocemento" of the Italian structural engineer Pier Luigi Nervi. In the São Carlos School of Engineering at the University of São Paulo (EESC—USP), ferrocement technology has been adapted to Brazilian conditions. Since the 1960s, the 'São Carlos Group', the research group formed for the study and development of ferrocement or reinforced mortar, made decisive steps in optimising this technology and its consequent consolidation.[16]

However, in this article, above all, we seek to present the recent advances in research that made possible to unite ferrocement or reinforced mortar developed over 60 years in Brazil to new digital manufacturing technologies, in order to contribute to establishing the foundations for their practical application in Brazil and other similar contexts, as described below.

Fig. 2 SARAH Rehabilitation Hospitals Network — SARAH Macapá and SARAH Fortaleza.[17]

Digital Fabrication Technologies and the Concept of Place

Digital manufacturing is the result of a continuous process of inserting digital technologies not only into products, but also into industrial automation processes throughout the second half of the twentieth century, and now into the twenty-first century.

Innovations related to the introduction of these technologies have been presented as disruptive, as they may represent an opportunity for paradigm breakdown, which will have a significant impact on the market and the future economic activity of companies, as well as on the basis of present social structure. It is also an answer to the exhaustion of a productive cycle originally based on classic Fordist standards, boiling down to the announcement of digital manufacturing as the trigger of the Third Industrial Revolution.

On the other hand, under the label of maker culture, there is the idea that, based on the concept of do-it-yourself (DIY), a kind of rebirth of the counterculture is happening, linked to anti-system social movements which broke out in the 1960s, especially in the USA, and are now linked to the emergence of the new digital manufacturing technologies. The movement would be able to overcome old contradictions of capitalist society, such as the exploitation and alienation of labour, while enjoying the benefits of digital technologies in design, production, circulation and consumption of goods.

Gershenfeld, who in his iconic book *FAB: The coming revolution on your desktop – From personal computers to personal fabrication* ponders the fact that, thanks to the convergence between computing and fabrication, today it is possible to convert bits into atoms, printing objects from their images or virtual modelling.[18]

Recently, Gershenfeld adds: "Digital fabrication will allow individuals to design and produce tangible objects on demand wherever and whenever they are needed. Widespread access to these technologies will challenge traditional business models, international cooperation and education."[19]

Despite the lively enthusiasm that nurtures the expectations of Gershenfeld and the adepts of the maker movement, whose ecosystem is the worldwide network of digital fabrication laboratories known as Fab Lab, it is worth emphasising a certain technicist, uncritical and ahistorical feature that is still observed in these environments, marked by an unshakable faith in state-of-the-art technologies and little concern with reflecting on what Antunes and Braga classify as the emergence and global scale growth of "infoproletariat" or "cyberproletariat."[20] From this perspective, the information sector, which makes intensive use of new technologies and is considered one of the most dynamic and daring sectors of the contemporary economy, refers to "working conditions [...] as precarious as the workers from the 19th century."[21]

18 Neil Gershenfeld, FAB*: The coming revolution on your desktop – From personal computers to personal fabrication* (Cambridge, MA: Basic Books, 2005).

19 Idem., "How to Make Almost Anything: The Digital Fabrication Revolution," *Foreign Affairs*, vol. 91, no.6 (November/December 2012): 43-57.

20 Campos and Henrique José dos Santos Dias, "A insustentável neutralidade da tecnologia: o dilema do Movimento Maker e dos Fab Labs" [The unsustainable neutrality of technology: the dilemma of Maker Movement and Fab Labs], *Revista Journal*, vol.14, n.1 (May 2018): 33–46; Ricardo Antunes and Ruy Braga, eds., *Infoproletários – degradação real do trabalho virtual* [Infoproletariat – real degradation of virtual work] (São Paulo: Boitempo Editorial, 2009).

21 Antunes and Braga, *Infoproletários*, quoted in Campos and Dias, "A insustentável neutralidade da tecnologia."

22 Campos and Dias, "A insustentável neutralidade da tecnologia."

Finally, the question posed is to grasp all new forms of labour exploitation and technology appropriation processes as problems that occur in different ways in central and peripheral countries, and so with very different characteristics and complexities. Even though the maker movement presents alternatives of interest regarding its emancipatory dimension, it is clear that it cannot be placed as a universal solution to local problems with different complexities.

In turn, to understand the existence of a popular economy, which is, by definition, self-managed, points to a possibility—to some extent due to a fracture in the hegemonic system—of using technological tools from the maker movement as dialogical mediation among different social actors, with the aim of strengthening local cultures and potentialities.[22] Therefore, it is necessary to establish, as a programmatic variable of this alternative, the connection between technology and the territory where it is being introduced, respecting, consequently, the differences and specificities of each location. It is not by chance that the territorial question is deliberately ignored by the ideo-political model that presented itself as an alternative to the welfare state, due to globalisation that flattens the complexity of local social life.

The digital technologies of the maker movement can greatly contribute to the development of the popular economy, as a fundamental piece in social processes of emancipation. Through network formation, mediated by rapid communication of problems and solutions, the digital prototyping of three-dimensional physical models can be an extremely useful instrument, since it can foster information flow and technology transference, facilitated by the web. CNC machines enable local prototyping and production of objects designed in different places.

The remarkable growth in the appropriation of these technologies can be illustrated by Brazil's first Fab Lab implantation in 2011: The Fab Lab SP in the FAU–USP, in São Paulo. Today, eleven years later, the country already has more than one hundred laboratories registered and spread throughout national territory (according to the platform fablabs.io).

Since 2015, the city of São Paulo has also the largest public network of digital fabrication laboratories in the world: the municipal network Fab Lab Livre SP (Free Fab Lab SP). There are 13 laboratories currently implemented, many of them located in peripheral areas. These laboratories offer various workshops, accessible to any citizen who wishes to participate, and support the execution of several projects developed by civil society with technical assistance. For this reason, the experience of these fab labs, as a public facility, has shown more coherence and effectiveness in the face of problems discussed here. It is interesting to note how democratisation of access to advanced technologies present in these laboratories came to be seen as an acquired social right.

Municipal laboratories also have potential to become local articulators of public administration, since they can group different spheres of government when serving citizens, establishing new centralities in peripheral areas and mutually reinforcing actions of different fields, such as health, education, culture, science and technology.

As a consequence, since the inauguration of Fab Lab Livre SP municipal network, these public laboratories have been functioning as platforms for social projects that seek to solve local problems, especially the ones located in peripheral communities of São Paulo. As a case study, we will focus on the project "Resilient Society, Resilient Design", which assembles several actors from academia, public institutions and within the local community to offer technical training workshops for residents of precarious settlements in São Paulo.

The project aims, by means of training people in socially vulnerable situations, to create an autonomous production cycle of precast lightweight systems and components to promote urban improvements along with economic development of the region.

In this sense, it is essential to rethink the role of technology in the context of peripheral countries and understand how digital fabrication tools can assist social processes in solving problems that are largely bound to the territory and the local scale.

Case Study

Even before the global economic crisis caused by the Covid-19 pandemic, Brazil's accelerated impoverishment drove several families from large urban centres to precarious living conditions without basic infrastructure such as sanitation. This phenomenon can be observed especially in peripheral areas of major cities like São Paulo, where in recent years there has been an increase in the amount of informal settlements and slums. In neighbourhoods located near the banks of the Tietê river, the lack of basic infrastructure is aggravated by major floods during the rainy season, which implies an urban, social and environmental degradation of this territory.

One of the most endangered areas near the Tietê river is Jardim Pantanal, a neighbourhood that, being in an environmental protection zone, does not have access to regular public services nor basic sanitation. In addition, the permanent residence of the population and their sense of belonging is often threatened by fear of expropriation, since land ownership is an unresolved issue due to environmental protection laws.

Despite the constant threat of expropriation, the local population is known for joining forces to carry out urban upgrading initiatives in so-called "*mutirões*" or mutual aid initiatives. For instance, one "*mutirão*" was performed to lay out pipelines for distributing drinking water inside the neighbourhood. However, since most of the streets in Jardim Pantanal are neither asphalted nor paved, the drinking water pipelines become uncovered and damaged over time, causing water contamination (Figures 3).

Fig. 3 [opposite page] Manima Street in Jardim Pantanal neighbourhood, São Paulo, 2017 (authors' photo).

As a highly organised community, Jardim Pantanal inhabitants concentrate around civil society institutions, such as AMOJAP (Association of Residents and Friends of Jardim Pantanal), whose ultimate goal is to achieve land regularisation for the local population. With the aim of carrying out urban upgrading projects to improve the quality of life of Pantanal's residents, the DIGI–FAB (digital fabrication technologies for the production of contemporary design and architecture) research group from FAU–USP, under the coordination of Prof. Paulo Fonseca de Campos, initiated the "Resilient Society, Resilient Design" research project alongside AMOJAP. Its objective was to create two building systems for the urbanisation of precarious settlements: one modular sidewalk for rainwater drainage and another for popular housing.

Both building systems were designed as lightweight prefabricated ferrocement components, an easily replicable and low-cost technology, so that they could be produced by the community itself. The proposed idea was to implement a small production unit in Jardim Pantanal that doubled as a teaching centre, where local residents could learn how to execute lightweight prefabrication and use it to improve their own neighbourhood. Bearing in mind that public investment in this region is scarce, this kind of enterprise could be sponsored by the government as a viable alternative to large construction companies.

To carry out the "Resilient Society, Resilient Design" project, the methodology adopted was based on a practical approach. The DIGI–FAB research group held weekly meetings at Fab Lab SP (FAU–USP) to design and experiment with ways to incorporate digital manufacturing tools in the formwork process so as to enable technology transfer of the process as a whole. Reduced-scale and life-size models were prototyped using CNC drilling machines and laser cutters to test assembly process, fitting and material resistance.

According to the initial premises of the project, by incorporating digital fabrication into the production process of lightweight prefabricated elements, it would be possible to rely on the precision and speed of CNC machines instead of traditional carpentry tools.

One methodological aspect that should be emphasized here is the participatory process of the AMOJAP team. Periodical visits to Fab Lab SP were scheduled so AMOJAP members could see the prototypes and machinery in action, as well as input suggestions to improve the initial design. Additionally, DIGI–FAB researchers would often visit Jardim Pantanal to assess and discuss local issues regarding floods, public spaces, housing and urban infrastructure.

This approach was instigated by the already mentioned implementation of 13 public Fab Labs in the city of São Paulo, the Fab Lab Livre SP Network (Figure 4), as a social and digital inclusion initiative. Thus, in addition to producing lightweight prefabricated elements, residents of Jardim Pantanal would be able to assemble their own wooden formwork in nearby public Fab Labs, as well as share the digital files with other communities who wish to do the same.

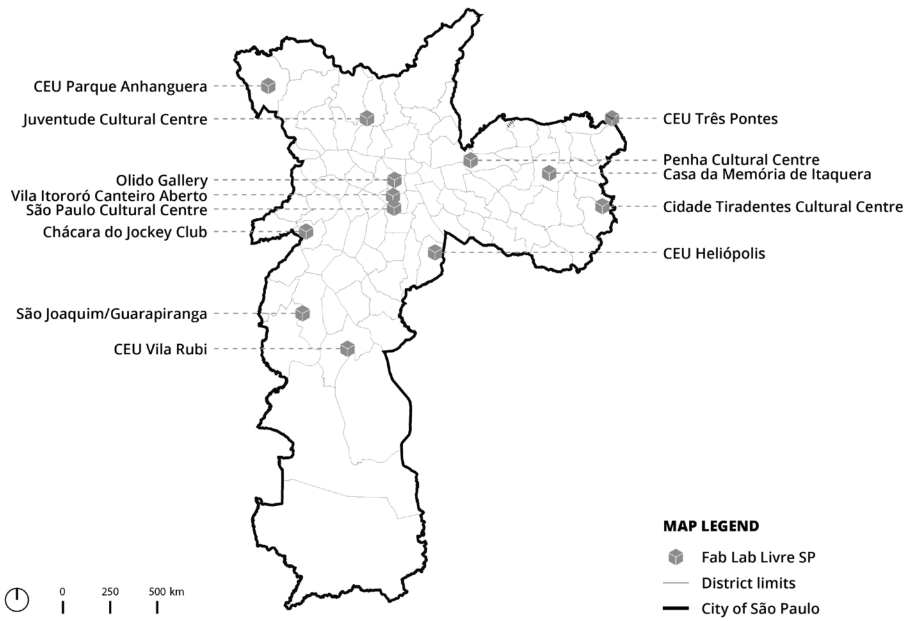


Fig. 4 Fab Lab Livre SP Network, São Paulo, 2022 (elaborated by the authors).

Therefore, the activities undertaken at Fab Lab SP (FAU–USP) and at the public Fab Labs Livres SP in the East Zone of São Paulo (CEU Três Pontes, Itaquera and Cidade Tiradentes) would develop a complementary type of research, focused on digital modelling and fabrication tools. It is believed that, in the long run, this link with Fab Labs could encourage new community projects and partnerships with university research groups.
In this context, the university can act in convergence with other local public policies, integrating them with civil society initiatives committed to social welfare and promoting digital fabrication as a tool for innovation through social transformation.

Modular Sidewalk for Rainwater Drainage

The first building system proposed by DIGI–FAB research group was a prefabricated modular sidewalk designed to drain and correctly dispose of rainwater, as a means of surface water drainage. Complementarily, it also performs as an urban reordering instrument, defining and separating circulation flows in public spaces. Basically, the building system consists of two main components: the gallery, a prefabricated element made of high-performance ferrocement; and the sidewalk, made of conventional reinforced concrete (Figures 5).

In addition to rainwater management, the modular sidewalk system can house urban infrastructure pipelines, doubling as a service

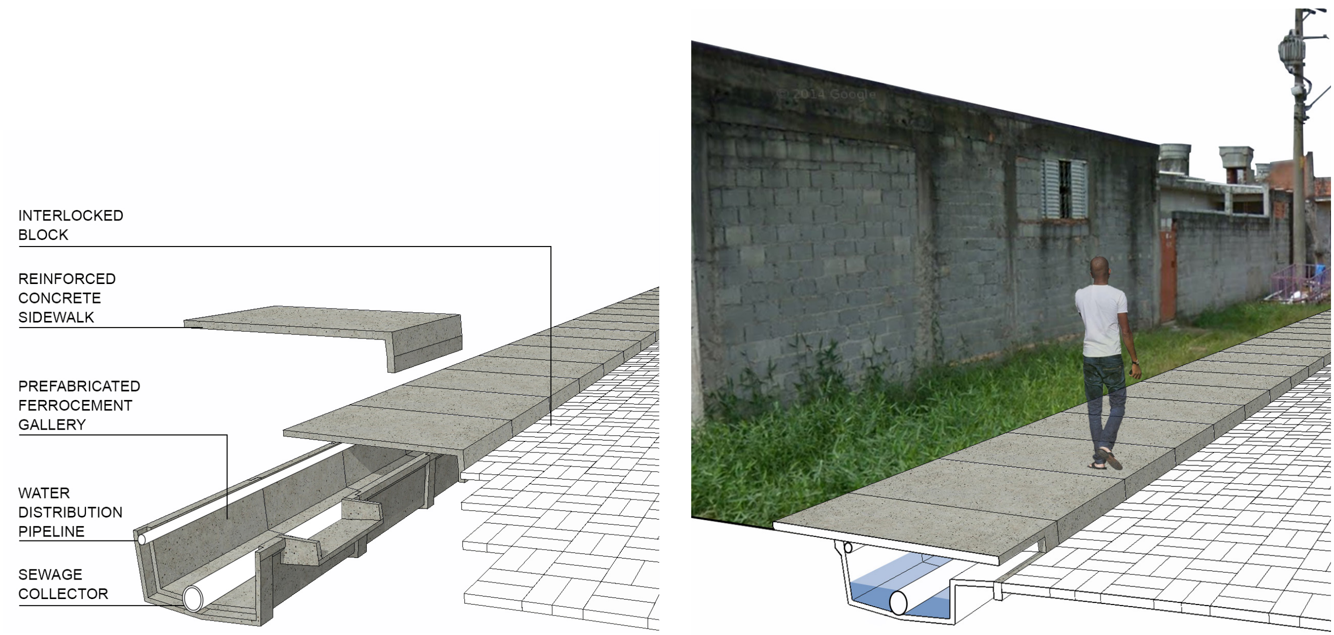


Fig. 5 Modular sidewalk building system components (left) and implementation (right), São Paulo, 2017 (elaborated by the authors).

23 Fonseca de Campos, *Microconcreto de alto desempeño: la tecnología del MicroCAD aplicada en la construcción del hábitat social [High-performance microconcrete: the microCAD technology applied in the construction of social habitat]*, (São Paulo: Mandarim, 2013).

gallery. Due to the lack of basic sanitation in Jardim Pantanal, this use is of vital importance considering the public health agenda, as it protects water distribution pipelines and accommodates a sewage removal network. Thereby, in addition to avoiding drinking water contamination, it is possible to remove all waste water discharge that is currently being disposed of near the population.

This approach was based on a previous project called "Aceras Drenantes" (Drainage Sidewalks), formulated in Uruguay by Prof. Paulo Fonseca de Campos, in 2006 (Figures 6). Conceived within the Irregular Settlement Integration Programme (PIAI), its main goal was to create a social programme associated with productive ventures that could be managed by the residents of a peripheral community.[23] During the Uruguay experience, although there was no continuation of the project, a prototype of the sidewalk module was designed and executed on a 1:1 scale.

Recognizing its technical potential and social reach, DIGI–FAB research group remodelled the 'Aceras Drenantes' project to incorporate digital fabrication processes as a way to disseminate high-tech tools in architecture and construction. The first step was to adapt the original formwork design in traditional carpentry as a digital model to be executed by a CNC milling machine. In Brazil it is traditional to use wooden formwork for reinforced concrete, therefore 18 mm-thick marine plywood was adopted as the base material as it has great structural resistance and durability.

The practical research was carried out in FAU–USP's Fab Lab SP, where several scale models and prototypes were developed and presented to AMOJAP representatives, resulting in a 1:1 prototype made of marine plywood (Figures 7).

To further the discussion and participation of Jardim Pantanal residents, a local workshop was organised to test the user experience of assembling the proposed formwork using a set of instructions and laser cut small-scale models (Figures 8). The place chosen for the workshop was intentionally a site near the Tietê river, a piece of land which local children use for recreational activities. This site was indicated by AMOJAP as a possible location for the small production unit, so the workshop was also an opportunity to associate the project with the place.

[opposite page]

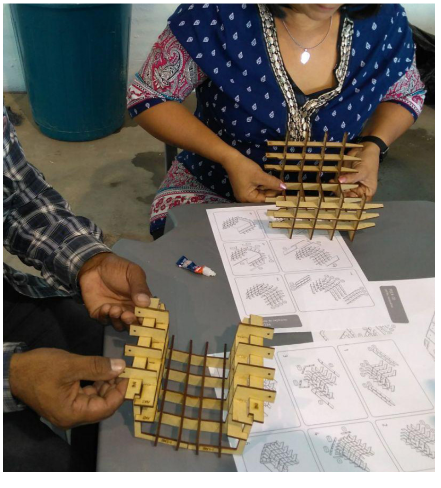
Fig. 6 "Aceras Drenantes" (Drainage Sidewalks) 1:1 prototype, Uruguay, 2006 (Paulo Fonseca de Campos' photo).

Fig. 7 1:1 scale prototype of the plywood formwork in Fab Lab SP, São Paulo, 2017 (authors' photo).

Fig. 8 Workshop in Jardim Pantanal with local residents, São Paulo, 2018 (authors' photo).








24 Amanda de Souza da Silva, "Jardim Pantanal: atores e interesses, desalento e esperança [Jardim Pantanal: actors and interests, discouragement and hope]" (Masters Thesis., EACHUSP, 2016), 17–20.

25 Mutual Aid Housing Cooperative action that took place in Vila Nova Cachoeirinha neighbourhood, São Paulo.

Precast Building System for Housing

Jardim Pantanal neighbourhood, as already mentioned, suffers from major floods during the rainy season which, in the most severe cases, could lead to partial or complete destruction of houses.[24] Although they are not frequent, these events aggravate local residents' quality of life and may affect the health and financial stability of these families.

Bearing in mind their aspiration for permanence and a consolidated life, the DIGI–FAB research group suggested the development of a building system for popular housing units that offered a safe and habitable level during floods by raising the ground floor. This proposal was based on previous well-known examples of settlements that coexist with water, such as riverside villages in the Amazon river, stilt houses in mangroves near the coast of São Paulo or wetlands in the southern region of the United States.

For this purpose, the housing unit model "Housing Prototype One" (Figure 9), originally built in the "Mutirão Cachoeirinha Leste" ("Cachoeirinha" Mutual Aid Housing Cooperative), was used as a reference for structure and layout.[25] The building system was developed by the Urban and Social Equipment Development Centre (CEDEC) at São Paulo Municipal Urbanisation Company (EMURB) and relies on prefabricated ferrocement profiles—beams and pillars—that are later concreted in loco. Since it is a self-supporting structure, the walls can be made from any material available, from concrete blocks to plywood. Keeping up with the proposed production logic, all formwork for prefabricated ferrocement components should be done following the same process as the previous project—3D modelling in computer software and a CNC milling machine.

Fig. 9 "Housing Prototype One" for Cachoeirinha Mutual Aid Housing Co-operative, São Paulo, 1989 (Paulo Fonseca de Campos' photo).

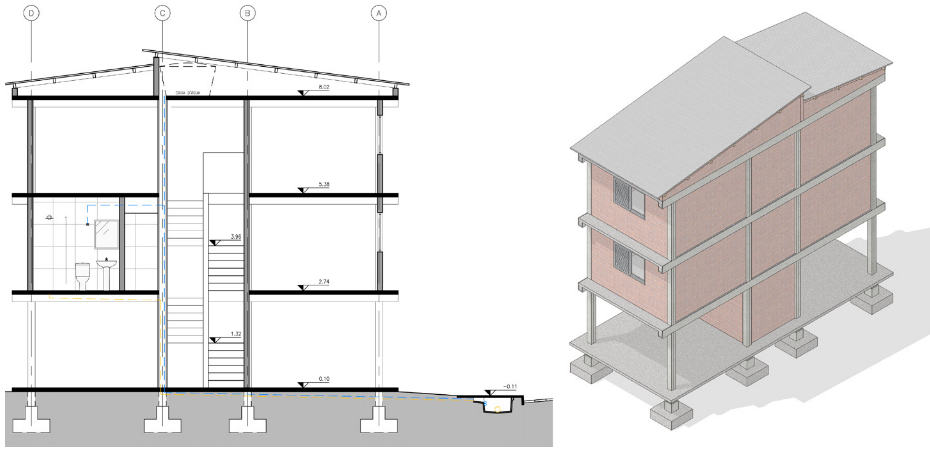


Fig. 10 Housing unit proposed (right), in the longitudinal section (left), all layout modifications are visible, São Paulo, 2017 (elaborated by the authors).

Maintaining the same structural design, adaptations were made to keep the house habitable during intense floods. One of the most important changes was elevating all wet areas — bathroom, kitchen and laundry room — to the upper floor (Figures 10). As a result, the resident family would be able to maintain its daily habits during floods, such as cooking and personal hygiene, a difficulty reported by the population of Pantanal.[26] Another significant adaptation was the introduction of a vertical circulation core in the housing unit, allowing its construction as terraced houses, a common building typology in this region.

Lastly, the ground floor should preferably house external activities only, such as a parking garage, laundry or recreation area in order to prevent water damage or material losses. However, on the condition that the resident is aware of the consequences, the ground floor could be occupied with closed rooms and even a small family business, a typical activity in irregular settlements.

Final Considerations

This article seeks to demonstrate the viable use of ferrocement lightweight prefabrication combined with the new digital manufacturing tools through applied research in the field of social habitat in Brazil. Both the use of ferrocement lightweight prefabrication and the adoption of digital manufacturing tools were based on a series of design requirements to be met.

Firstly, lightweight prefabrication within a model of community production emerges as a technology with high added value that can

26 Nayara dos Santos Egute, “Quando a água sobe: análise da capacidade adaptativa de moradores do Jardim Pantanal expostos às enchentes [When water rises: an analysis of the adaptive capacity of Jardim Pantanal residents exposed to floods]” (PhD thesis, FSPUSP, 2016), 87–157.

improve conventional building methods. However, when inserted into a scenario of mutual-aid building practices, this technology can play an important social role as an enabler that, insofar as it is accompanied by a technology transfer process, can emancipate the marginalised population so they can act for their own interests.

Within this proposal, ferrocement technology is as an economically feasible alternative. Thanks to the popularity of reinforced concrete in Brazil, all materials required for ferrocement lightweight prefabrication can be easily found in any region. Also, transfer of this technology is facilitated by prior technical knowledge in reinforced concrete. As a result, the initial investment for a prefabricated ferrocement component production unit, or the adoption of this technology in existing companies, is considerably reduced. Nonetheless, possibly the greatest benefit of this building method is its fast and easy execution, enabling public policies that are more efficient in meeting the demands of the population for urban improvement.

Secondly, the incorporation of digital manufacturing tools could be interpreted as a revision of the proposal for São Paulo's context, in which there is a goal to democratise access to information and the replication of productive processes. With this in mind, the local community is expected to be able to work with digital fabrication tools in order to fully appropriate the productive process. For this purpose, the digital technology transfer process will take place in public laboratories in the Fab Lab Livre SP Network, since it provides free technical courses — aimed at teaching how to work with digital fabrication machines and modelling software — and free use of the machinery.

All things considered, we can say that this article proposes a serious reflection on the impacts caused by the introduction of digital manufacturing technologies in peripheral countries such as Brazil, mainly through the so-called international maker movement.

In this sense, it can be seen that the universal conceptions and solutions originated from the maker movement, when disembarking in peripheral countries, do not assure a critical appropriation of digital technologies.[27] In addition, it is concluded that the maker's promise to overcome alienation and exploitation of labour can hardly be fulfilled without an in-depth understanding of the conflicting interests involved in these power relations, which place economic power in opposition to the majority of society interests. There are no chances for the (fallacious) speech: "win-win!"

Despite the enthusiasm fuelled by the maker movement, the ecosystem which the worldwide network Fab Lab is part of, it is not reasonable to consider that the digital fabrication technology would lead to an overcoming of capitalism with new post-capitalist conditions of labour.[28] Projects can be downloaded from a website and produced at home. It remains to be seen, as Bonsiepe says, if with this method of design

27 Fonseca de Campos and Dias, "A insustentável neutralidade da tecnologia".

28 Gui Bonsiepe, "Desobediencia Proyectual" [The Disobedience of Design] (speech at the symposium *Can design change society?*, Berlin, September 2015).

and production, design activity will become popular and what products will be manufactured: "We cannot exclude the possibility that it will end up in massive manufacture of bibelots."[29]

The dissemination of digital technology accelerated on a global scale can be interpreted as an essential part of a singular agenda in the current economic context. Contrary to what is often argued, the flexibilization attributed to such a model is not a means to increase numbers of those employed in labour. In the words of Antunes "... it is an imposition on the labour force so that lower wages are accepted and in worse conditions," by providing informal job openings that spread irregular, precarious work without guarantees.[30]

In addition, there is a striking fact that has been occurring in parallel with the automation of industrial processes, which is the intangibility of the new format adopted to expand the hegemonic economic model, as well as its territorial unlinking, substantively due to financialization of the economy and expansion of the service sector. These two phenomena combine the circulation of various 'commodities' such as increasingly digitized and networked information flow. According to Castillo, among other factors, the immaterial nature of the raw material used in this process demands new forms of organization in high technology contexts, so as to allow information circulation and common intervention — for example, something that is no longer conditioned by physical, geographical, national or other barriers. Organizations consisting of real collectives and virtual "teams" acting in a network are physically located thousands of kilometres away, and sometimes are equally culturally distant.

In this sense, the dominant ideology, according to characteristics already mentioned, relates social life to a logic of such a fragmentary nature that it ends up suppressing the minimal possibility for collective construction in society, in favour of an individualist conception of the subject. Individualist entrepreneurship, according to this view, is a fundamental cog in the functioning of the neoliberal economy. In peripheral countries, fragmentation of social relations inhibits more autonomous cultural construction and links them to central countries according to a logic of dependence.[31]

This article, however, is concerned with the use of the word "empowerment" in the deepest Freirean sense possible, as a synonym of social emancipation, since liberation is a social act and not a process of an individual nature (self-liberation).[32] It is in this context that the maker movement — which is often associated with a new pattern of training presented as maker education or "hands-on" education — is frequently viewed within individualized conceptions of empowerment and entrepreneurship.

Finally, it can be said that digital technologies of the maker movement, generically classified as digital fabrication, have the potential

29 Ibid.
30 Antunes, "Desenhando a nova morfologia do trabalho; As múltiplas formas de degradação do trabalho", *Revista Crítica de Ciências Sociais*, no. 83 (2008): 19–34.
31 Campos and Dias, "A insustentável neutralidade da tecnologia".
32 Paulo Freire and Ira Shor, *Medo e ousadia; o cotidiano do professor* (Rio de Janeiro: Paz e Terra, 1986).

for dialogical mediation between popular culture, technical assistance services, civil society and the state. Therefore, it is urgent, mainly in the socio-economic context of peripheral countries, to experiment with methodological alternatives involving this type of technology from the perspective of assisting social emancipation processes. This is the specific contribution of the case study introduced in this article, as a possible means to advance in a community-based digital paradigm.

José P. Duarte
School of Architecture
and Landscape Architecture

Gonçalo Duarte
Department of Architectural
Engineering

Nate Brown
Department of Architectural
Engineering

Shadi Nazarian
School of Architecture
and Landscape Architecture

Ali Memari
Department of Architectural
Engineering; Department of Civil
and Environmental Engineering

Sven G. Bilén
School of Engineering Design,
Technology, and Professional
Programs

Aleksandra Radlinska
Department of Civil and
Environmental Engineering

The Pennsylvania State University,
University Park, PA, USA

Designing a Habitat for 3D Concrete Printing in Permafrost Regions

3D concrete printing has the potential to provide a solution to the global shortage of affordable housing. This technology may be particularly suitable for remote regions, where the shortage of labour and materials presents acute challenges. While most projects have focused on the use of the technology to fabricate a structure's walls, this article describes a research effort aimed at printing the entire enclosure using only 3D concrete printing. The design of a habitat for the permafrost regions of Alaska is used as a case study. The design approach was to conceive a parametric housing system based on modular units whose form is inspired by traditional vault design and is amenable to 3D concrete printing. The proposed design is governed by structural and architectural features, the addressable volume of the robotic arm printer, the desire to avoid formwork, environmental factors such as thermal requirements, foundation type in response to the permafrost, and loads on the structure. While the size of each modular unit is determined by spatial requirements, its exact shape is defined using optimization following structural, thermal, and printing considerations. The printing of a reduced-scale version of the proposed unit validated the design, showing its printability.

Keywords
— additive construction, design for 3D printing, 3D concrete printing, 3D-printed houses, cold-climate design

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Introduction

The world's population is at 7.97 billion people today and growing, with 900 million living in informal settlements with inadequate living conditions.[1] By 2025, these figures are expected to reach 8.2 billion and 1.8 billion, respectively, making the urgency of addressing the current global shortage of homes even more critical. Reducing the severity of this situation requires the development of innovative design and construction technologies. Additive construction technologies, specifically 3D concrete printing (3DCP), can help address the current housing shortage, while also augmenting or transforming the construction industry. In simplified terms, in 3DCP, a 3D model of the part to be printed is used to generate a series of instructions to control an automated fabricator. The 3D model is first sliced into layers, typically horizontal, and then these layers are decomposed into linear or curved patterns, which are linked together to form a continuous toolpath. The toolpath is traversed by a nozzle extruding the material, to create a physical version of the digital model.[2]

Modern additive manufacturing was invented in the 1980s in Japan by Hideo Kodama, who invented two AM photopolymer rapid prototyping systems, in which a mask pattern controls the UV exposure area.[3] Then, in 1983 Charles Hull invented stereolithography, a form of 3D printing technology in which light causes chemical monomers and oligomers to form polymers.[4] Since then, many other forms of 3D printing have been developed. Initially, 3D printing was aimed at developing prototypes of parts and, thus, called rapid prototyping; only later was it oriented towards the development of fully functional parts. The introduction of 3D printing in architecture occurred in the mid-1990s at MIT when a fused deposition model (FDM) machine was acquired and explored both in teaching and research. One of the first applications of this machine was to produce models of Palladian villas and other architectural elements.[5] Then, in 1997 at Rensselaer Polytechnic Institute in New York, Joseph Pegna introduced 3DCP technology.[6] In the following year, at the University of Southern California, Khoshnevis et al. developed contour crafting, in which the key idea was to print the contour of walls, then place reinforcement bars or cages, and finally pour additional concrete to surround the reinforcing elements in place.[7] In 2009, Lim et al. at Loughborough University in the United Kingdom created a simpler process for 3DCP.[8] Since then, research in 3DCP has grown exponentially at different universities, government agencies, and within companies around the world.[9]

The promise of 3DCP stems from a number of potential advantages. By enabling the automated fabrication of parts directly, each from potentially different 3D models, 3DCP enables mass customization, which can lead to higher-value outcomes and thus user satisfaction. For the construction industry, automation translates into lower labour requirements, which can lead to increased safety, lower construction times, and lower construction costs. With 3DCP it is possible to extrude composite functionally graded

1 Worldometer, "World Population," accessed September 18, 2022. https://www.worldometers.info/world-population/
2 Ian Gibson, David Robson, Brent Stucker and Mahyar Khorasani, *Additive Manufacturing Technologies*, third edition (Cham, Switzerland: Springer Nature, 2021). https://doi.org/10.1007/978-3-030-56127-7
3 Petar Kocovic, "Chapter 1 – History of Additive Manufacturing," in *3D Printing and its Impact on the Production of Fully Functional Components: Emerging Research and Opportunities*, ed. Petar Kocovic (Hershey: IGI Global, 2017), 1–24.
4 Idem.
5 Larry Sass, *Reconstructing Palladio's villas: An analysis of Palladio's villa design and construction process,* PhD thesis (Cambridge: Massachusetts Institute of Technology, 2000), 385.
6 Joseph Pegna. "Exploratory investigation of solid freeform construction," *Automation in Construction*, vol. 5, no. 5 (February 1997): 427–437. https://doi.org/10.1016/S0926-5805(96)00166-5
7 Behrokh Khoshnevis, Satish Bukkapatnam, Hongkyu Kwon, Jason Saito, "Experimental investigation of contour crafting using ceramics materials," *Rapid Prototyping Journal*, vol. 7, no. 1 (March 2001): 32–42. https://doi.org/10.1108/13552540110365144
8 Seung Hyun Lim, Thanh T. Le, John Webster, Richard Buswell, Simon Austin, Alistair Gibb, Tony Thorpe, "Fabricating construction components using layered manufacturing technology," in *Proceedings of the Global Innovation in Construction Conference*, Loughborough, UK, 13–16 September 2009, 512–520.
9 Fuyan Lyu, Dongliang Zhao , Xiaohui Hou, Li Sun and Qiang Zhang, "Overview of the Development of 3D-Printing Concrete: A Review," *Applied Sciences*, vol. 11, no. 21 (October 2021): 9822. https://doi.org/10.3390/app11219822

materials (FGMs), for which the gradient of component materials can vary in response to functional requirements. With concrete this can be realized, for example, by partially replacing river sand with cork granules as the aggregate in response to insulation requirements, thereby avoiding the construction of complex wall assemblies involving multiple layers and many trades.[10] Thus, the use of FGMs can simplify construction processes, requires fewer joints (reducing building pathologies and lowering maintenance costs), increases safety, and lowers construction times and costs. FGMs can also enable optimized environmental performance and material savings, resulting in energy savings and, therefore, lower operating costs and a reduction in the ecological footprint. 3DCP also avoids the use of formwork, which allows the creation of complex forms and intricate surface textures at no additional cost, which increases design freedom. Finally, 3DCP facilitates the use of construction materials derived from in situ resources, which results in reduction of transportation requirements, thereby decreasing cost, CO_2 emissions, and ecological footprint. In summary, 3DCP enables the construction of affordable, customized, high performance, and aesthetically pleasing buildings, while increasing safety, reducing construction time, and lowering environmental impacts.

The application of 3DCP in the construction of structures for commercial purposes has followed three fundamental strategies. The first strategy involves parts of the building being 3D printed in the factory or on site and then put in place. This avoids having to deal with constraints imposed by the printing system, such as limitations of the printing envelope or the need for formwork when printing overhangs. An example of this approach is the house printed by the Chinese company Winsun in 2014.[11] The second strategy is similar to the first, except that the walls are printed in place and the roof is either built with another material (e.g., wood) or pre-printed and hoisted into place. Some recent examples include a two-story house by Kamp C in Westerlo, Belgium in 2020; a house built for Habitat for Humanity by Alquist in Virginia, USA, in 2021; a detached 94 m^2 single-storey home with two bedrooms built by TU Eindhoven in the Netherlands in 2021; and House Zero by ICON in Arizona, USA, to name a few examples of 3DCP homes.[12] In this context, most 3DCP approaches to date have mainly focused on the construction of walls. The third strategy, however, is to fully print the entire structure in place. The demonstration of a 3D-printed house by the Italian company Wasp using clay in 2021 included two interconnected dome-shaped structures, which were topped by prefabricated skylights to completely enclose them.[13] Two years earlier, a Penn State team participating in the NASA 3D Printed Mars Habitat Challenge successfully printed a concrete structure comprising two interconnected cylinders transitioning to cones at the top, resulting in the first fully enclosed structure printed at architectural scale.[14] This paper describes research building on that effort with design of 3DCP homes in remote permafrost regions of Alaska, describing various aspects of design.

10 Flávio Craveiro, Helena Bártolo, A. Gale, José Duarte and Paulo Bártolo, "A Design Tool for Resource-Efficient Fabrication of 3D-Graded Structural Building Components Using Additive Manufacturing," *Automation in Construction*, vol. 82 (October 2017): 75–83. https://doi.org/10.1016/j.autcon.2017.05.006

11 Lucy Wang, "Chinese Company Assembles 3D-Printed Concrete Houses in a Day for Less Than $5,000 each." April 6, 2014 https://inhabitat.com/chinese-company-assembles-ten-3d-printed-concrete-houses-in-one-day-for-less-than-5000-each/ Last accessed November 7, 2022.

12 e-architect, "3D-Printed Model Home by Kamp C in Westerlo." https://www.e-architect.com/belgium/3d-printed-model-home-kamp-c-westerlo. Last modified July 7, 2020.
Architizer, "House Zero." https://architizer.com/projects/house-zero/ Last accessed September 18, 2022.
Matt Hickman, "Habitat for Humanity and Alquist Partner for the East Coast's First 3D-Printed Habitat Home," *The Architects Newspaper*. Last modified July 7, 2020. https://www.archpaper.com/2021/07/habitat-for-humanity-alquist-partner-east-coasts-first-3d-printed-habitat-home/
Eindhoven University of Technology, "Printing our way out of the housing crisis: 'It is desperately needed,'" April 30, 2021. https://www.tue.nl/en/news/news-overview/30-04-2021-printing-our-way-out-of-the-housing-crisis-it-is-desperately-needed. Last accessed November 7, 2022.

13 Wikipedia, "Tecla House," *Wikipedia*. https://en.wikipedia.org/wiki/Tecla_house. Last modified August 8, 2022.

14 Penn State, "Designing Sustainable Homes on Mars and Earth." https://www.psu.edu/impact/story/designing-sustainable-homes-mars-earth/. Last modified April 8, 2019.

15 Gonçalo Duarte, Nathan Brown, Ali Memari, and José Duarte, "Learning from Historical Structures under Compression for Concrete 3D Printing Construction," *Journal of Building Engineering,* vol. 43 (November 2021): 103009. https://doi.org/10.1016/j.jobe.2021.103009

16 Nicholas A. Meisel, Nathan Watson, Sven G. Bilén, José Duarte and Shadi Nazarian, "Design and System Considerations for Construction-Scale Concrete Additive Manufacturing via Robotic Arm Deposition," *3D Printing and Additive Manufacturing*, vol. 9, no. 1 (February 2022): 35–45. http://doi.org/10.1089/3dp.2020.0335

Precedents

The goal of the proposed design and construction approach was to develop an expedited method for providing affordable housing to indigenous peoples in Nome, a community in a remote area of Alaska. The design approach was based on two sets of precedents. The first is a set of vernacular examples from Alaska, including igloos built in ice and mountain shelters built using dry stack stone. The common theme in both cases is the use of block-layering techniques, which constitute a "primitive" form of additive construction. However, whereas for igloos the blocks are laid in radial layers with a capstone, in mountain shelters the blocks are laid out in horizontal layers. Such techniques can be found in many other cultures around the world. The second set of precedents consists of historic examples from erudite architecture, namely vault-and-dome construction techniques. These include structures based on Roman and gothic arches that were also built following brick- or stone-layering techniques. Particularly, the Gothic arch constituted a suitable precedent, as the degree of inclination of the dome's walls is higher, which constitutes an important restriction when printing concrete without formwork. Several types and domes were studied, and the cross-vault was selected, as described further below. A more detailed discussion of using vernacular and erudite vault-and-dome construction techniques as a precedent for printing enclosing structures can be found in Duarte et al.[15]

System Constraints, Design Requirements, and Design Approach

The design approach was to conceive of a parametric housing system based on modular units with shape and configuration suitable for 3D printing of the entire structure—including grounding, walls, and enclosure. The proposed shape is impacted by the features of the printing system, the desire to avoid formwork, applicable loads on the structure (self-weight, snow, wind, earthquake), and thermal requirements for the structure and the foundation type, as well as spatial requirements of the home. Constraints associated with the printing system included the reach of the robotic arm in x, y, and z directions above and below ground, the maximum printing angle, and the associated minimum wall thickness. For a description of the printing system, see Meisel et al.[16] Formwork was avoided to simplify construction, decrease material waste, and lower construction cost. Structural requirements included the need to avoid collapse of freshly deposited concrete during printing without the use of any temporary support, and the ability to resist vertical and lateral loads after the concrete hardens. Thermal requirements included isolating the structure to create a comfortable living environment in the interior and to avoid heat transfer between the structure and the supporting ground to avoid melting the permafrost soil, which could endanger the structure.

17 CCHRC, "Remote — A Manual," Cold Climate Research Center, 2013. http://cchrc.org/library/remote-manual

18 USDA, "Alaska Rural Homeownership Resource Guide," U. S. Department of Agriculture, 2017.

19 HUD, "Alaska Native Housing Needs," Outreach Session Proceedings Report, Office of Native American Programs, U.S. Department of Housing and Urban Development, 2011.

The resulting design is a modular unit with approximate dimensions of 12 × 12 × 16 ft (approx. 3.7 × 3.6 × 4.9 m) and inspired by historic cross-vault structures with pointed arches to avoid exceeding the maximum printing angle. The dimensions are a compromise between printing constraints, height of the interior space, and spatial programme and requirements. The idea is that one unit could meet minimal programmatic requirements (kitchen, bedroom, etc.) or be combined with other units to accommodate larger spaces (living room, etc.). Parametric variation of one unit is also possible within the constraints imposed by the printing system. Several variations of the structural unit are being considered for further development. For the initial foundation, one solution foresees creating an open crawl space to allow air circulation between the top of ground and the underside of the structure, with concrete columns printed on top of wooden or steel piles that extend through the active layer and into the permafrost zone or down to bedrock. The other solution consists of a thermal raft slab-on-grade foundation such that crushed rocks and insulation assist in avoiding the transfer of heat to the permafrost. Above this foundation, one option consists of a double shell structure with an insulation layer of foam in between, and the other a single shell with the insulation layer on the inner side of the structure. While the size of each modular unit is determined by spatial requirements, the exact shape is defined following optimization based on both the structural and thermal performance considerations.

Review of the Conventional Home Construction in Rural Alaska

Home building in Alaska should consider various challenges, including harsh environmental conditions due to snow and frozen ground, as well as wind and earthquake loads. Moreover, energy efficiency and health considerations are also of primary interest. Many guides and manuals have been developed by the Cold Climate Housing Research Center (CCHRC)[17] with the objective of guiding all stakeholders in the design and construction practices that consider various critical aspects for construction in Alaska. Furthermore, given that 40% of the Alaska's 300 rural communities are in areas without much access to infrastructure — including roads, clean water, and sewers — healthy home construction is of critical importance for people living in those regions.[18]

The project reported in this paper explored for the first time the feasibility of using 3D printing in rural Alaska. A review of the vernacular architecture in Alaska made clear that it was built such that not much fuel would be needed to keep the inhabitants warm.[19] However, the influence of modern American home construction techniques that were not developed for extreme cold conditions have negatively impacted quality of life. The walls, floors, and roofs have details that result in thermal bridges, which lead to loss of significant interior heat through conduction.

In addition, these houses have been costlier to build and maintain because they are hermetically sealed and prevent the flow of fresh air, thus requiring air conditioning systems. Lack of access to fresh air and breathing in circulated interior air accumulates interior air pollutants over time — such as mould caused by moisture and humidity built up, bacteria, and cleaning chemicals — which collectively cause and exasperate chronic respiratory illnesses, creating an unhealthy living environment.[20] In addition, much of the required wood for construction purposes has to be imported, which means more expensive construction.

Review of Foundation Systems Used in Alaska Home Building

Residential buildings in Alaska use both shallow and deep (i.e., pile) foundations. In suitable soil conditions, shallow foundations may be placed directly in contact with the frozen ground, but more often the requirement to maintain thermal equilibrium in the frozen ground dictates that shallow foundations be placed on a gravel berm or a layer of suitable sandy soil, preferably with, but sometimes without, insulation.[21] Pile foundations do not require open excavation, which can significantly disturb the permafrost. Structures supported by piles are elevated above the ground surface to prevent heat loss through the floor from warming the frozen ground, and to allow cold air to refreeze the active layer in the winter. Proper consideration of the interaction between the building and the frozen ground in the permafrost zone is necessary to guarantee a successful design of the home. Permafrost is frozen ground with temperature below 32°F (0°C) for over two consecutive years. However, if the permafrost layer starts to experience heave due to the repeated thaw-freeze cycle, the foundation and the structure can have settlement causing damage to the structure. Therefore, the design needs to prevent the heat transfer between the structure and the soil to maintain the bearing capacity of the supporting soil.[22]

Structural System Definition

The focus of the structural system study was on a solution that permitted the 3D printing of a full continuous concrete shelter to avoid structural joints as much as possible. Given the current state of the art in concrete printing, the objective was to find solutions that avoided complex reinforcement solutions. The study thus developed design solutions with compressive stresses as the main load-resisting mechanism in the walls that could be printed without formwork; the use of carbon or steel fibres mixed with the concrete was selected as an appropriate reinforcement for the compression-dominated design to control shrinkage and thermal cracks in the structure.

After a study of conventional structures, a set of solutions was selected for further study during the first stage of our explorations (Figure 1).[23] All these solutions had a footprint of 12 × 12 ft

20 CCHRC, "Remote—A Manual," Cold Climate Research Center, 2013. http://cchrc.org/library/remote-manual.

21 Orlando Andersland and Branko Ladanyi, *An Introduction to Frozen Ground Engineering* (New York: Springer, 1994). https://doi.org/10.1007/978-1-4757-2290-1

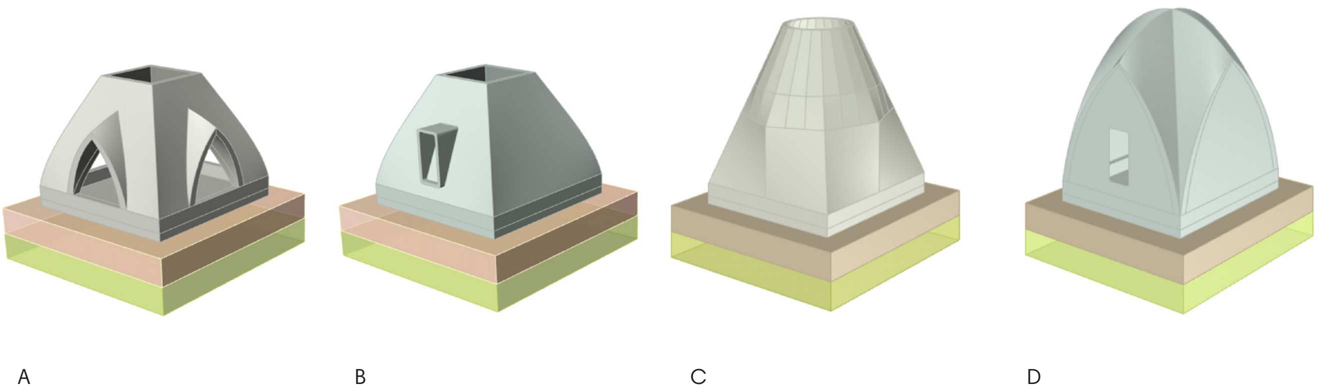
22 Terry McFadden, *Design Manual for New Foundations on Permafrost* (North Pole, AK: Permafrost Technology Foundation, September 2000).

23 Duarte et al, "Learning from Historical Structures."

(approx. 3.6 × 3.6 m) and a height between 8 and 13 ft (approx. 2.4 m and 3.9 m), since printing fully enclosed spaces requires either a dome or arch to remain in compression, or a prefabricated flat element on top. While the solutions shown in Figure 1 are all assumed to be slab-on-grade, the same structures were also considered as elevated options. As noted in the introduction, the proposed designs benefit from the full potential of 3D printing and maximizing automated construction. The main advantages of printing the full structure, including grounding, walls, and roof, are (1) simpler and cheaper construction, and (2) having fewer joints, thereby decreasing the likelihood of air and moisture leaks, which is particularly important in harsh environments like Alaska. Each printed structure may constitute a single-space shelter, a tiny house for a small household, or a room of a house for a larger household that could be composed of several units clustered together and a small loft space depending on the internal height of the enclosure.

Solutions A and B in Figure 1 have the same basic shape for the roof structure, a so-called cloister dome. Both solutions have a truncated top due to printing restrictions, which could contain a skylight. They differ in the way openings are introduced, with Solution B requiring the use of prefab elements for making horizontal flat surfaces. Solution C is based on a traditional dome shape from ancient Persia called a squinch, which transitions from a square footprint to a domical space, with some advantages in terms of 3D printing. Solution D is based on a cross-vault with pointed arches and is the tallest of the four structures, but it is also the one that is fully enclosed at the top. This range of solutions demonstrates the design flexibility of 3D printing. Based on preliminary evaluation of the four options in terms of feasibility, Solution D was selected for further development.

Fig. 1 Selection of structures with vaulted roof structures for further study: slab on grade version with foundation consisting of floating slab supported directly over the active layer. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.



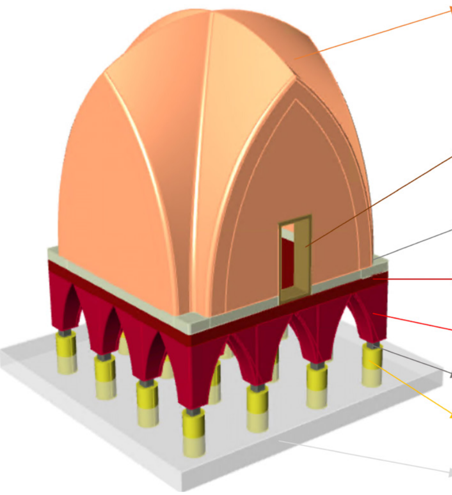


Fig. 2 The different parts potentially composing the 3D printed monolithic vaulted structure: foundation, grounding, slab, walls, and roof. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

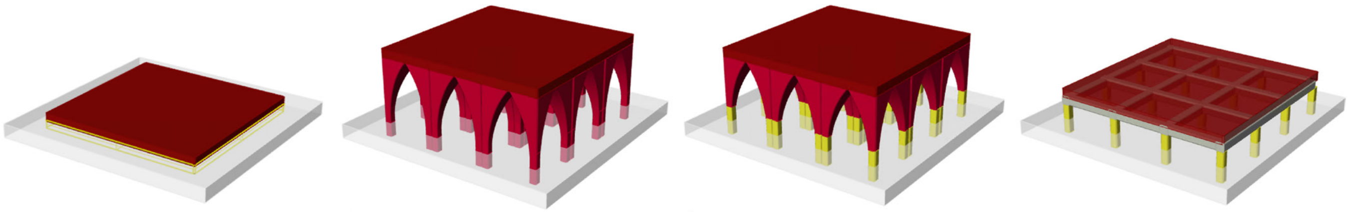
24 Naveen K. Muthumanickam, José P. Duarte, Shadi Nazarian, Ali Memari, Sven G. Bilén, "Combining AI and BIM in the design and construction of a Mars habitat," in *Routledge Companion for AI in Architecture*, eds. Imdat As and Prithwish Basu (Abingdon, UK: Routledge, 2021), 251-279.

Parametric Design

These structures can be potentially composed of foundation, grounding, slab, walls, and roof (Figure 2). The parametric definition of the structure allowed for a quick exploration of possible design alterations such as changing the height, curvature, footprint, openings, and foundation shape in response to structural, aesthetic, or functional requirements.
This parametric model was implemented in Grasshopper and Rhino and constituted the generative module of a larger design platform powered by artificial intelligence (AI), which will also include a structural and thermal simulation module and an optimization module.[24] This platform permits one to analyse the trade-offs between different solutions and to find those with better performance from the selected structural and thermal viewpoints. This extended design platform and its use in the design of a scale version of the cross-vault unit is briefly described further below.

Foundation

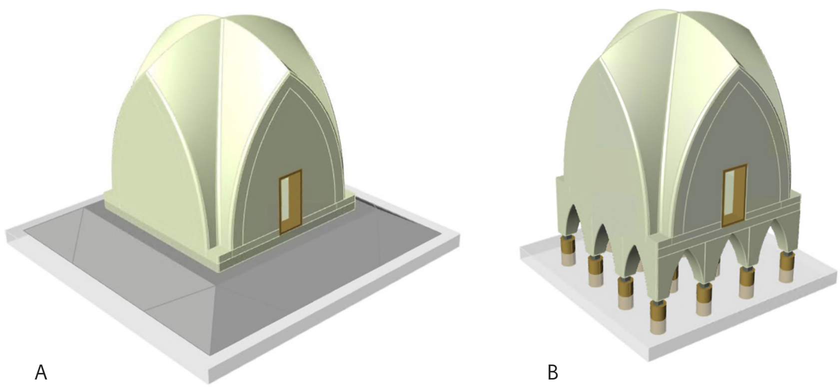
Four solutions were studied for the foundation (Figure 3). The first solution consists of a floating slab supported directly on the ground (Figure 3A). This configuration presents difficulties posed by the heat of the concrete material during printing and curing, which may cause heat transfer to the permafrost soil. In addition, this configuration makes it difficult to thermally isolate the interior, which is warmer when occupied, from the permafrost soil layer. It is possible to overcome these difficulties with the design of the foundation, consisting of a bed of crushed stone deposited on grade and placing a rigid insulation layer prior to printing. The thermal resistance and thickness of the rigid insulation will be determined to avoid heat transfer



A B C D

to the ground (Figure 3B, C, and D). However, raising the main structure would be more effective. This approach creates an isolating air cavity (as in an open crawl space) between the warmer, inhabitable structure and the frozen permafrost soil underneath. Following this approach, the second solution for the foundation is to print pillars to form the entire foundation both above and below grade (Figure 3B). This solution requires the printing system to reach several metres deep into the active layer and within the permafrost region and presents the disadvantage of the deposited material, which is hot while curing and, as mentioned above, may cause heat transfer and potential melting of the soil in the permafrost region. Thus, this solution is not a desirable option due to thermal and structural challenges. In the third solution (Figure 3C), the piles are made of another material — wood or steel — placed into the ground and topped by small platforms on which the 3D-printed vaulted concrete grounding would be printed. In the fourth solution, (Figure 3D), a concrete slab platform would be printed on top of a wooden or metal bed supported on piles, creating a "podium" on which the structure can be printed, which requires additional materials that could reliably support the 3D-printed structure. Thus, Solutions A and C were considered for further design development (Figure 4).

Fig. 3 Solutions for the foundation: (A) floating 3D printed slab on ground, (B) slab on 3D printed concrete grounding on piles in the same material, (C) slab on 3D printed concrete grounding on piles in other material (wood or steel), and (D) concrete slab 3D printed on cable grid structure.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.



A B

Fig. 4 The structure considering two different foundation solutions: (A) slab on grade and (B) raised slab.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

Grounding

The grounding is the part of the structure that creates an isolating air cavity between the inhabitable structure and the ground surface underlain by active and permafrost layers, something like a crawl space. It consists of a set of cross-vaulted shapes supported on the wooden or steel piles in Solution c of Figure 3. The goal of the design is to enable as much airflow as possible through the cross vaults while still transferring the structural loads of the floor slab above down into the individual piles below. These geometric trade-offs were analysed, and the constraints for the height needed to create sufficient ventilation were considered, while limiting the height to reduce lateral seismic induced forces in the columns. Two different approaches were considered to create this crawl space. In the first approach, the grounding is printed, and in the second, it consists of a graded slab mounted on the piles, on the top of which the concrete slab would be printed. This hybrid solution can simplify printing but would lead to a more complex shelter by involving other construction systems. Therefore, the first approach was selected for the design. Considering the height needed for the curved arch shape of the supporting columns, the result was to minimize the height of the pile above ground surface to about 0,6 m, with the rest of the height for ventilation provided by the printed columns for a total open space height of about 1,5 m above the ground surface. The shape of the grounding could be made of "homogeneous" printed concrete material or "heterogeneous" material with an exterior shell made of stronger, heavy concrete and the interior core made of lightweight concrete, in which sand aggregates of the shell are partially replaced by light expanded clay or cork granules, which has the advantage of producing a lighter structure with increased insulation properties. The latter solution has two options: in the first option, the inner lighter concrete is poured or printed after the outer shell is printed, whereas in the second option, the outer shell and the inner lighter core are printed simultaneously using a FGM printing strategy, where the aggregate content of the mixture is changed during printing. The second solution requires a more sophisticated (and, hence, more expensive) printing system. In addition, the added insulation provided by mixing cork or other insulation granular materials would be minor compared to the level of R-values needed for Alaska. Therefore, foam insulation was considered in the design as explained below.

Slab

The slab is the part of the structure that rests on the grounding and mediates between the grounding and the interior. It provides a flat, horizontal basis for the floor of the shelter. It may be made of ordinary homogeneous concrete or, alternatively, functionally graded concrete as described above, which also brings additional benefits, including lighter weight (which benefits the foundation design and lowers seismic loads) and a lower carbon footprint. While such a solution is ideal for most climates, it is quite challenging to design parameters that will provide the desirable thermal resistance for the concrete. Therefore, even though an FGM could be used in an Alaskan construction project, significant supplemental insulation would still be needed.

Walls

Walls are the vertical elements that enclose the interior space. Because of the vaulted shape of the roof, the printed walls can be short, providing just a basis for the roof. Two possibilities were considered for the structure of the walls: solid (single shell) or hollow (double shell) (Figures 5 and 6, respectively). The former may use homogeneous concrete or functionally graded concrete with insulative "layers" with an increased grade of lightweight material towards the top (with the potential benefits mentioned earlier), and the insulative aggregates printed on the exterior side of the wall. The latter has the advantage of being lighter, using less material,

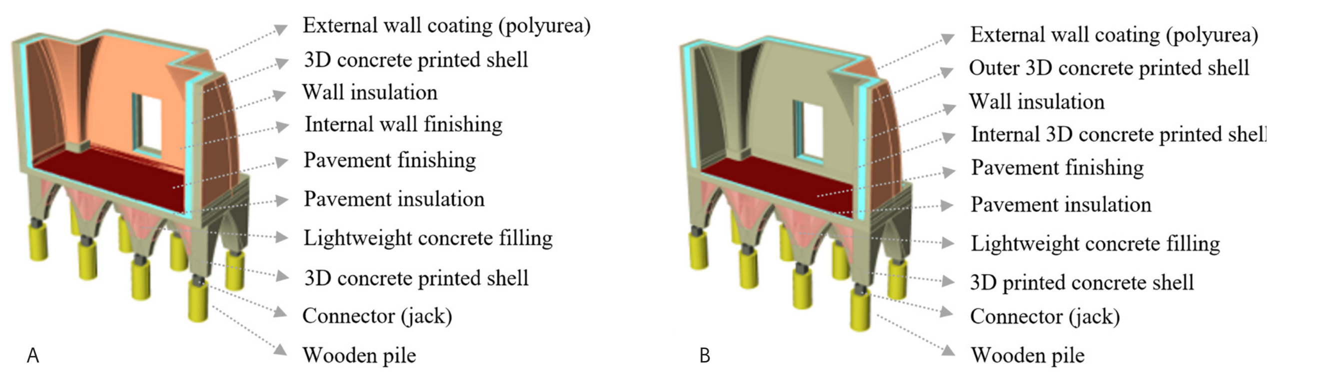


Fig. 5 Wall solutions considered for the raised slab structure: (A) single shell and (B) double shell. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

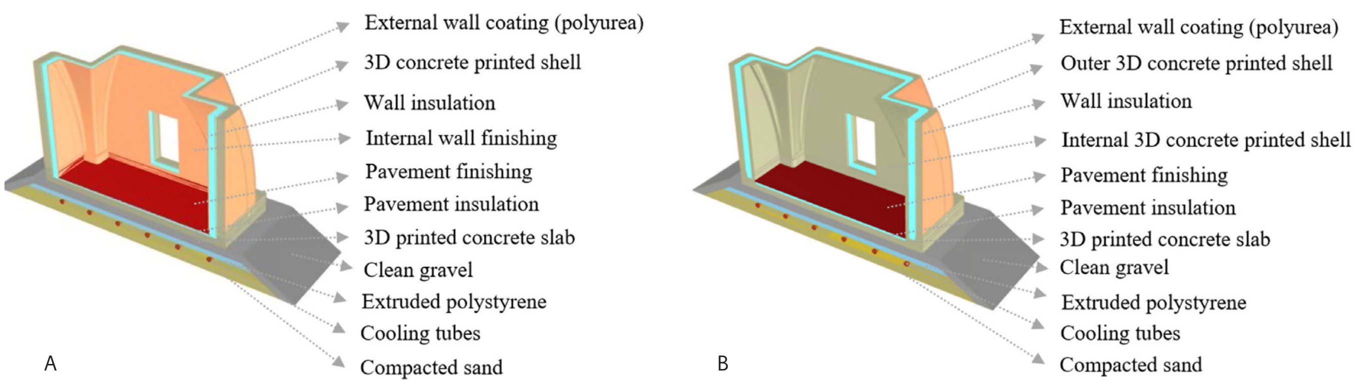


Fig. 6 Wall solutions considered for the slab on grade structure: (A) with single shell and (B) double shell.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

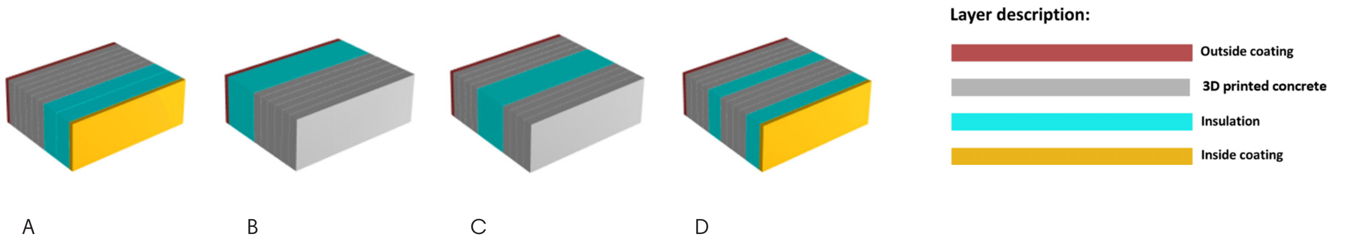
and having improved insulation properties, but it makes printing of the vaulted roof on the top more challenging. The hollow cavities maybe filled in with insulation foam or granules, but this hybrid solution complicates construction. Further study will permit identification of the most appropriate solution considering structural, thermal, printing, and construction elements.

Roof

The roof is the part of the structure that encloses the interior space. As mentioned above, using a vaulted or domed structure for the roof permits 3D printing of the entire structure, avoiding formwork, simplifying construction, and providing a unibody, sealed-and-enclosed environment by decreasing the number of joints. The exact shape of the dome will be determined after structural analysis and considering printing constraints, including the reach of the robotic arm and toolpath design. Like the remaining parts of the structure, the roof may be printed using ordinary concrete or lightweight concrete, which could be homogeneous or potentially functionally graded, with the grade of lightweight aggregates increasing toward the top for improved structural performance.

Envelope and Insulation

In addition to the structural requirements, the extreme environmental conditions in Alaska necessitate careful consideration of the building envelope and its performance. As noted above, a major requirement is thermal separation of the conditioned indoor space from the foundation to avoid melting the permafrost. In addition, the surface temperature of the floor is of particular concern in Arctic climates, since it impacts the liveability of the house and requires the floor surface temperature to be as close to the ambient temperature as possible. The walls and roof also have stringent insulation requirements. For the Alaskan climate, the required R-values range from around R-20 for above-grade walls to around R-50 for roofs, depending on the geographic location. In traditional rectilinear construction, such values could be achieved through a variety of methods. The proposed geometries for 3D printing the proposed structures require different strategies due to their curvature and gradual transitions between the wall and the roof. Given these challenges, several insulation approaches were considered. In addition to the conventional single material use in all layers, FGM offers a solution to integrate insulation materials (e.g., cork granules or Styrofoam balls) into the concrete to improve various properties and attributes, including being lightweight, which favourably affects structural and seismic design and improves thermal resistance and ecological footprint. However, since concrete itself generates less than R-1 per inch (approx. 2.5 cm) depending on density, other insulating materials are required. One possibility is to spray foam on the interior shell or on the exterior shell, which can adhere to custom shapes and offer R-values



25 Nathan Brown, José Duarte, Ali Memari, Ming Xiao, Shadi Nazarian, Gonçalo Duarte, and Zhengyu Wu, "A Comparison of Thermal Insulation Strategies for 3D Printed Concrete Structures in Cold Regions," *Proceedings of the 6th RBDCC – Residential Building Design and Construction Conference*, State College, PA, March 4–6, 2022.

of up to R-7 per inch (approx. 2.5 cm) for closed-cell foams (Figure 7A and B). Another option is to print double walls and roofs, which creates some structural advantages, and then fill the voids with insulative materials, either in the form of foam or rigid panels, depending on the geometry (Figure 7C). In this method, special care would be given to potential thermal bridging, which is subject to how the two layers are connected for structural load transfer. Another possibility is to employ a combination of strategies, that is, have a double wall shell with two layers of insulation, one in between the wall cavity and another on the interior shell (Figure 7D). For a complete discussion of insulation strategies, see Brown et al.[25]

3D–Printing System and Process

Two printing systems are necessary to implement the proposed design. The first is used to develop and test the concept at the laboratory scale. The second will be utilized to print the prototype of a house in Alaska. These two systems are briefly described below.

The laboratory printing system consists of a mixer-pump for mixing and extruding the dry mixture, a silo that contains the dry mix and feeds the pump, and an industrial six-axis robotic arm with a 2.8 m reach (Figure 8). The dimensions of the printing volume can vary depending on the length and orientation of extensions added to the robotic arm, which can be adjusted to be suitable for the size of the structural unit. To print larger structures, the system can be extended to include a large silo capable of storing enough of the dry mixture to print one structural unit, a water tank in case there is no water source near the construction site, and a second robot to install door and window frames in place. In yet another configuration, the system may include a second mixer-pump and a second silo, to enable the printing of FGMs. In short, in this version of the system, each silo holds a mixture with a different gradient and is connected to a pump, the mixtures from each pump are mixed with a dynamic nozzle,

Fig. 7 Potential thermal insulation strategies: considering the printing of a single (A and B) or a double shell (C and D) and the placement of the insulation layer (A) inside, (B) outside, (C) in between the shells, or (D) a combination of both. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

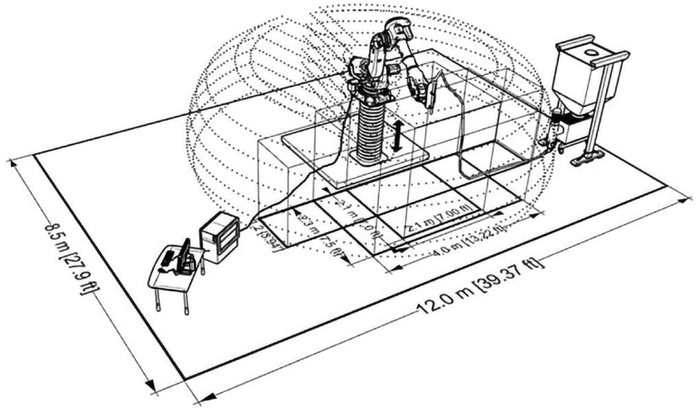


Fig. 8 Diagram of the basic configuration of the printing system in the laboratory, which includes a mixer-pump, a small silo, and a robotic arm. The printing area can be increased to meet the size of the proposed structural unit by adding an extension to the robotic arm.
Developed at Additive Construction Laboratory – AddCon Lab, PSU, in 2020, by Nate Watson.

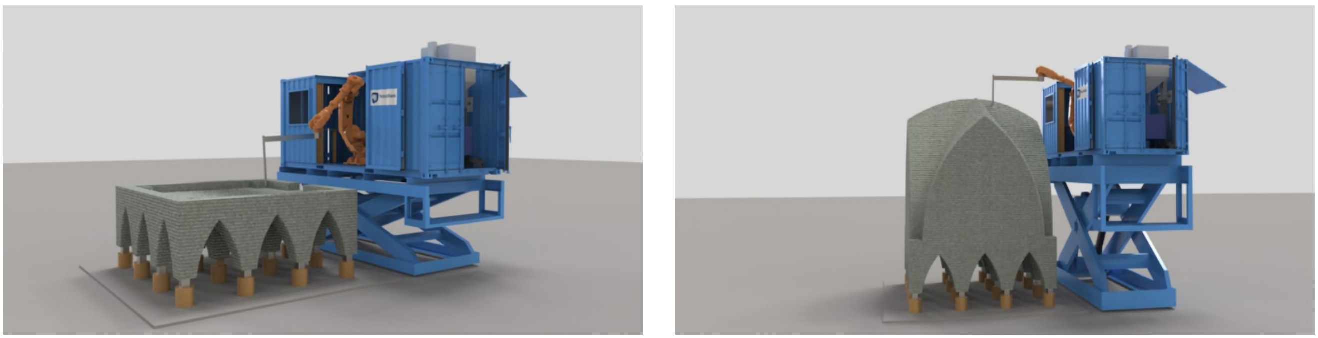


Fig. 9 Printing process of the proposed shelter at two different stages of completion. The depicted “printer-in-a-box” system is currently being developed to facilitate deployment and mobility.
Developed at Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Nate Watson.

and by varying the relative speed of each pump, it is possible to change the gradient of the printing mixture.[26]

The system being developed to print in Alaska is a revised version of the laboratory system, enhanced to overcome two of its limitations and enable the printing of full-scale structures on site. The first concerns the mobility of the system, for which two configurations are being studied. In the first, the system is redesigned into a “printer-in-a-box” system, so that it can be moved using standard shipping methods. As this configuration imposes some restriction regarding how the system can be moved on site, the second configuration foresees the robot being mounted on a rover. Figure 9 shows the printing of the proposed design with the first configuration.

26 Flávio Craveiro, Helena Bártolo, Paulo Bártolo, Shadi Nazarian, and José Duarte. “An Automated System for 3D Printing Functionally Graded Concrete-Based Materials,” *Additive Manufacturing*, vol. 33 (May 2020): 101146. https://doi.org/10.1016/j.addma.2020.101146

27 Gonçalo Duarte, José Duarte, Ali Memari, Nathan Brown, Juan Pablo Gevaudan, "Towards a model for buildability in concrete printing based on material properties," *Construction and Building Materials*. (Submitted on October 3, 2022).

Materials

Different kinds of mixtures for 3D printing, including cementitious, non-cementitious (i.e., geopolymer), and clay-based mixtures have been developed for various printing applications. More extensive work and testing has been carried out with cementitious mixtures, particularly a mixture developed in collaboration with Gulf Concrete Technologies (GCT). This mixture is a blend of ordinary Portland cement, lime, pulverized limestone, especially graded masonry sand, fibres, and admixtures with a maximum particle size of 1 mm (table 1).

MATERIAL COMPOSITION	PERCENTAGE
Pulverized limestone	<2–6%
Lime	<30%
Crystalline silica	<50–70%
Portland cement	<50%
Calcium sulfoaluminate cement	<5–12%
Cellulose	0.2–2%
Starch	0.2–2%

Tab. 1 GCT material composition.

Material properties of this mixture of concrete, including compressive strength, setting time, and flowability, are presented in table 2. The compressive strength of the material was tested in accordance with ASTM C-109. The Vicat needle test (ASTM C-191) was performed to measure the initial and final setting times and a flow table test (ASTM C-1437) was conducted to evaluate the flowability of the mixture. An ASTM C39 test obtained within 48 hours of printing the concrete structural elements and performed on a printed cylindrical specimen showed 749 psi compressive strength, and an ASTM C78 test performed on a printed rectangular beam showed 485 psi (modulus of rupture). Detailed information on the experimental programme conducted to characterize the material is provided in Duarte et al.[27] The main objective of this programme was to characterize the rheological and strength properties of the material over time.

COMPRESSIVE STRENGTH	TEST AGE (DAYS)	STRENGTH (MPA) [PSI]
	3	15.12 [2192]
	7	17.95 [2602]
	28	24.55 [3560]
SETTING TIME	INITIAL SET (MIN)	FINAL SET (MIN)
	80.7	143
FLOWABILITY	FLOW (CM)	
	23.3	

Tab. 2 GCT material properties.

28 Negar Ashrafi, Shadi Nazarian, Nicholas Meisel and José Duarte, “A Grammar-Based Algorithm for Toolpath Generation: Compensating for material deformation in the additive manufacturing of concrete,” *Additive Manufacturing*, vol. 55 (July 2022): 1–20. https://doi.org/10.1016/j.addma.2022.102803.

29 Gonçalo Duarte, José Duarte, Nathan Brown, Ali Memari, Juan Pablo Gevaudan, “Design for Early-Age Structural Performance of 3D Printed Concrete Structures: a Parametric Numerical Modeling Approach,” *Automation in Construction*. (Submitted on June 28, 2022).

This information was then used to develop a structural analysis software to predict the behaviour of fresh state concrete in structures during the printing process to inform the design with 3D printing in mind, as explained further below. The goal, however, is to develop and test printable mixtures out of local materials with appropriate rheological and strength properties.

Toolpath Design

Concrete printing involves a complex system of interdependent variables involving the printing system, materials, and design. Successful printing of stable and accurate structures depends on tuning the system to the correct combination of values for these variables. Structural stability is related to printing quality, which depends on variables related to the pump and robotic arm, which, in turn, are related to the properties of the concrete mixture. These variables determine the dry mix feed and water flow rates, which determine the water-to-dry-mix ratio and, together with the pump rotation speed and the nozzle size, determine the required robotic arm travel speed. Research has been performed to obtain this information and model the relationships among the different system variables.[28] This research informed the software development for automatically generating toolpaths that guarantee high print quality by accounting for material deformation (Figure 10), considering key printing settings, such as the extrusion flow rate, layer printing time, and the size of the part in terms of the number of filaments and layers.[29]

The toolpath design software is implemented in Rhino and Grasshopper. The Grasshopper plugin HAL also is used to convert the toolpaths to the high-level programming language used to control the industrial robots. The robots have two operating modes: manual mode, in which the manipulator movement is under manual control and the speed is reduced to a maximum of 250 mm/s; and automatic mode, in which the

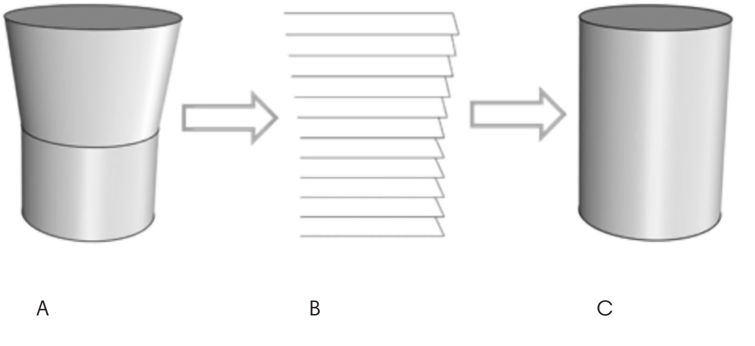


Fig. 10 Diagram representing the strategy for designing a cylinder with compensation for layer width deformation: (A) compensated designed cylinder, (B) compensated toolpath, and (C) resulting printed cylinder. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2020, by Negar Ashrafi.

safety function of the enabling three-position switch (one of the two safety functions of robots) is bypassed so that the manipulator can move without human intervention and the robot moves at full speed autonomously.

Construction Sequence

The construction of one unit with a double shell is depicted in Figure 11 for a raised-slab unit. The process starts with (A) the placement of piles into the permafrost soil followed by the jack connectors, then (B) proceeds with the printing of the grounding shell, which (C) is then filled with lightweight concrete. This makes the structure lighter, and if the lightweight concrete has insulating beads, it can provide some thermal insulation properties. Regardless, thermal insulation of the structure is provided in the interior. Next, (D) the floor slab is printed on top, then (E) the base wall, followed (F) by the placement of the opening frame. Then, (G) the printing of the roof structure is initiated, to (H) obtain the complete structure. In the solution

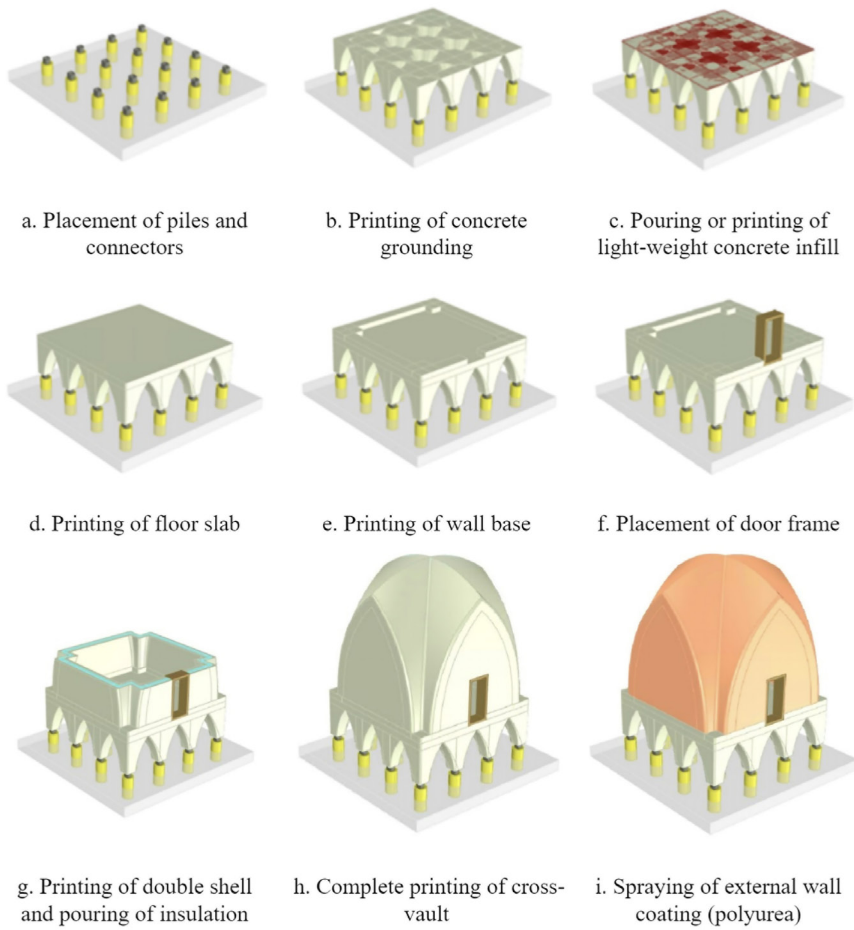


Fig. 11 Construction sequence of an elevated, cross-vault unit with double shell. The printing of shell and deposition of insulation in between may occur at the same time. The construction sequence of a unit with single shell is very similar, expect that insulation is placed after the shell is printed. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

with double shell, the insulation foam in between the two shells may be printed at the same time or sprayed after a certain number of layers are printed. Once the printing is over, (I) polyurea is sprayed on the exterior surface to provide waterproofing and protect the unit from abrasion or impact. In the solution with a single shell, construction proceeds much in the same way, except that insulation is sprayed after the shell is printed. As noted earlier, it is also possible to use rigid insulation on flat parts of the interior surfaces. Furthermore, insulation can also be milled to fit the curved shape of the shell and then mounted; this solution is more expensive and more delicate to build but provides a cleaner finishing.

Combining Units to Create Larger Houses

Larger houses can be obtained by incrementally adding new units (Figure 12). The printing of additional units can take place sequentially, one after the other, or over time, as the functional needs and financial ability of the

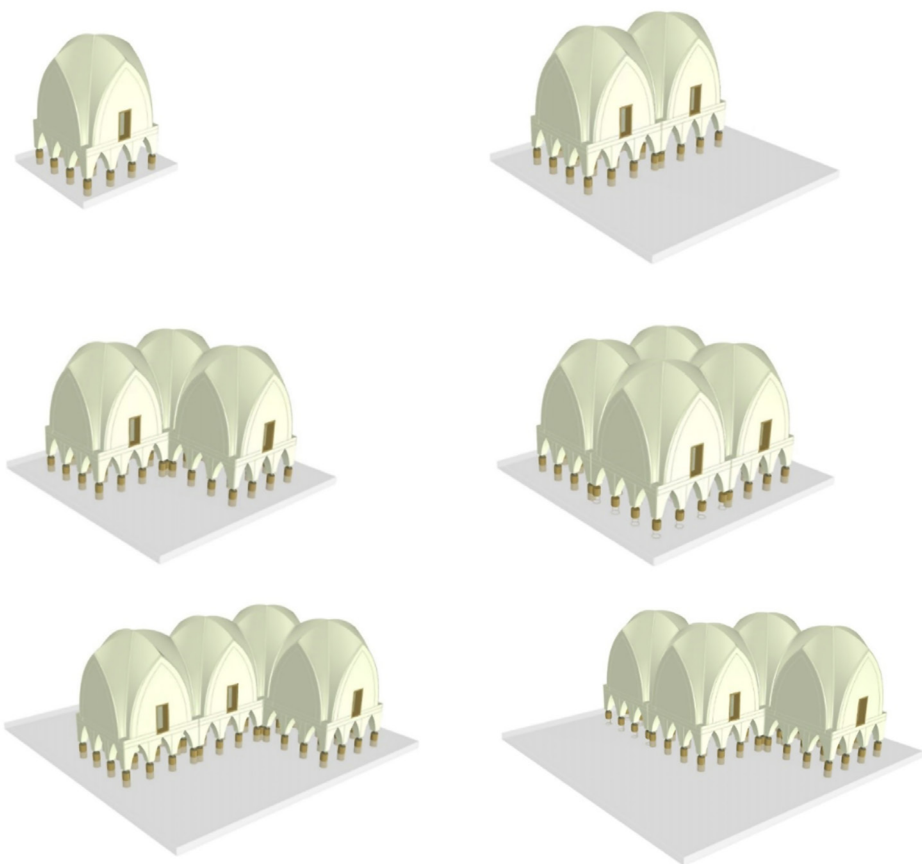


Fig. 12 Incremental addition of units to form larger houses, which may occur over time and take different configurations. Each unit may have different and one or more uses: kitchen, living-room, dining-room, bedroom, bathroom, and so on. The exact configuration and uses will depend on the household profile, including the number of members and social-economic level. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2021, by Gonçalo Duarte and José Duarte.

household increase. Houses may acquire different configurations as different number of units may be added on different sides. The possibility of combining units with different roof shapes is also noteworthy.

Optimizing a Scaled Unit Design

As noted in the section on parametric design, a platform was developed to optimize the design of vault structures. This platform supports a design optimization workflow for 3D concrete printed (3DCP) structures that comprises the following steps: (i) a generator of overall shapes, from a parametric model that was established based on shape grammar rules; (ii) a gradient-free constrained optimization process that uses 3D-printed concrete constraints to select the best designs and performs a partial structural analysis considering a preliminary toolpath to select the best solution; (iii) feeding of a refined toolpath for the best solutions; (iv) a simulator of the early-age structural behaviour that performs finite element analysis at each layer and checks whether the structure collapses during printing. The workflow was used in the design of an open cross-vault to print at one-third scale.

The constrained optimization was performed in Grasshopper using the component *Radical* from the plug-in *Design Space Exploration*. The optimization of the cross-vault structure consists of a typical constrained structural optimization problem, in which the objective is to minimize structural mass while subjected to a set of constraints. Four types of constraints were considered, namely structural constraints, toolpath constraints, geometric constraints, and system constraints. A more in-depth description of the optimization process is discussed in an upcoming publication.[30] Structural constraints comprised two types of sub-constraints: (i) serviceability sub-constraints that were expressed as a function of the lateral and vertical displacements when subjected, respectively, to a wind and deadload and serviceability load combination; and (ii) a proxy for printability that involved the finite element analysis of the largest identified cantilever at 35%, 70%, and 100% of its fabrication. The numerical modelling considered material properties, which would change every time a new layer is added, and the early age modes of collapse, namely, of plastic collapse, elastic buckling, and flexural collapse. Toolpath constraints considered two forms of constraints. First, a minimum acceptable printing time per layer in the counterweight region of 34 seconds is considered to filter solutions whose legs presented an excessively small cross-section area. Additionally, the algorithm of toolpath compensation for material deformation was implemented and automatically adjusted the toolpath design for layers with a printing time shorter than 34 seconds. Second, it included extrusion-based constraints, such as the material extrusion rate, as well as to the robot motion speed, which directly influence the extruded filament design. Geometry constraints included the maximum overhang criterion of 60 degrees,

30 Gonçalo Duarte, José Duarte, Nathan Brown, Ali Memari, Juan Pablo Gevaudan and Shadi Nazarian, "Structural Optimization of Overall Shapes in 3D Concrete Printing," (in preparation).

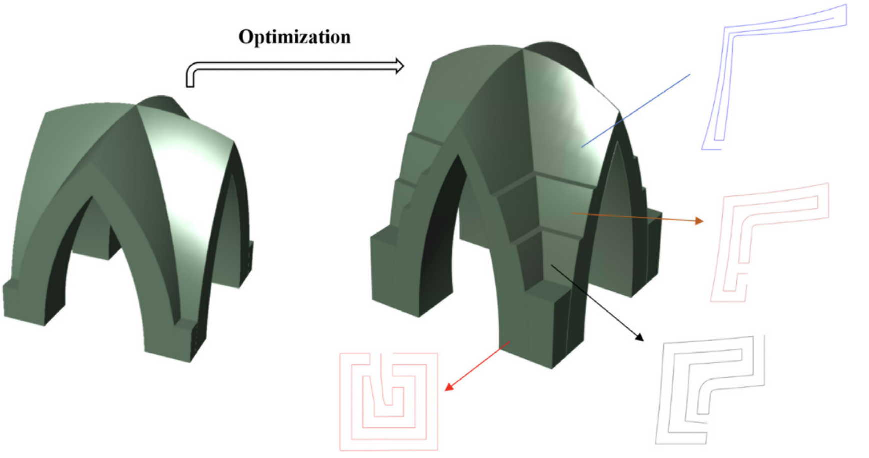


Fig. 13 Optimized design of a cross-vault unit to print at 1/3 scale and respective toolpath design at each stage of the leg fabrication. Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2022, by Gonçalo Duarte.

and system constraints limited the dimensions of the cross-vault to the printing envelope of the robotic arm, which resulted in a limitation of the length of the vault to be 1.20 m. The final design of the cross-vault with a height of 1.30 m and a length of 1.12 m, as well as the corresponding toolpath, which considers compensation for material deformation is presented in Figure 13.

Test Print of One Scaled Unit in Laboratory

To validate the design optimization process described above, the cross-vault was fabricated by printing one leg a time, until closing and respective top part. The goal of printing a complete leg at a time resulted from the decision of avoiding excessive travel moves, which would lead to additional printing time and material volume. The cross-vault was successfully printed (Figure 14), which validated the design approach and highlighted the potential of the 3DCP technology to fabricate enclosures.

Discussion and Conclusion

This paper describes the design of a habitat to be 3D printed in Alaska, where cold temperatures and permafrost soil pose significant challenges. In particular, it explains the design requirements that stem from the cold weather conditions and the constraints imposed by features of the printing system.

The shell design proposed for the envelope of the habitat includes foundation, walls, and roof. By continuously printing these construction elements, it is possible to decrease the number of joints and lower the

Fig. 14 Printed 1/3-scale prototype of the optimized cross-vault design.
Developed at Stuckeman Center for Design Computing – SCDC and Additive Construction Laboratory – AddCon Lab, PSU, in 2022, photo by José Duarte.

possibility of water and air leaks, thereby making it easier to maintain adequate living conditions indoors and avert building pathologies.
Of course, for the actual construction project, the potential for differential foundation settlement, thermal gradients, and structural overloads that can cause cracking would need to be considered in designing and developing the details. The proposed cross-vault design was selected after reviewing different vault designs inspired by historic structures, considering their printing feasibility, whether they fitted in the printing system's envelope, the ease of generating the toolpath, and the possibility of printing the roof. Two solutions for the foundation were selected after considering traditional solutions for cold climates, namely slab on grade and raised slab on piles. The latter seems to be better as it creates a "crawl space" in between the structure and the permafrost soil, preventing the heat from the interior heated space from melting the permafrost soil. Despite presenting increased printing difficulties, the preferred solution for creating the crawl space is to print several interconnected small vault-domes, filled with insulative lightweight concrete topped with a layer of insulation before printing the slab. Several solutions for insulating the walls and the roof were considered. As the extreme cold weather requires substantial thickness, it is not possible to meet insulation requirements by printing FGM alone, despite the architectural design benefits. The more promising solution is to print a double-wall shell with foam insulation in between, which would avoid difficulties in placing rigid insulation panels on to a double-curved form, while keeping the aesthetic qualities of the printed surface.

Two printing systems are being used to print the shell-shapes habitat designs. Both include a robotic arm, which presents increased design, six axes of freedom, and deployment flexibility when compared to gantry-based systems. The first printing system is fixed in place, and it is used to print prototypes, whereas the second system is a further evolved mobile version of the first that can be shipped in a container and/or mounted on a rover to print habitats on rugged sites. A platform incorporating generative, simulation, and optimization components was developed to support the design of the shell structure of the habitat. The generative component encodes the rules for designing vault and dome structures, as well as the toolpaths to print them, while considering the features of the printing system. The simulation part performs structural analysis of the selected design schemes, and it can be extended to include other forms of analysis, such as environmental comfort. The optimization component permits identification of various design solutions with better performance. This platform was used to design a one-third-scale prototype of the cross-vault that was successfully printed in the laboratory, thereby validating the approach.

It is noteworthy that the proposed design approach is supported by a multidisciplinary team of researchers with diverse scientific and cultural backgrounds, which adds to and enriches the depth of knowledge, as a necessary condition to successfully develop the technology. Research encompasses three main areas, including design of materials, design of the printing system, and exploring the necessary design processes with the goal to model the complex relationships among the various variables associated with these areas. The variables can be divided into six categories: environmental variables, material composition, material properties, printing settings, toolpath design, and building design. The ultimate goal is to develop a mathematical model of the printing process and to control it in order to achieve high printing quality and structural stability. This is mainly an applied research project based on the development of cases studies such as the one described in this paper, which is centred on the design aspects related to the 3D printing of housing in rural and permafrost regions of Alaska.

The described effort is only the starting point for developing the full design of a housing system. Future work will include detailing the interior design of the habitat, including technical installations; extending the design platform to incorporate thermal comfort; development of the mobile printing system; and running printing tests at full scale.

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Conflict of Interest:
Drs. Duarte, Bilén, and Prof. Nazarian own equity in X-Hab 3D, Inc., which has an interest in this project. Their ownership in this company has been reviewed by the University's Individual Conflict of Interest Committee and is currently being managed by the University.

Pedro Martins
Department of Architecture
of the University of Coimbra
and Faculty of Architecture,
University of Porto. DFL/CEAU/FAUP

José Pedro Sousa
Faculty of Architecture,
University of Porto. DFL/CEAU/FAUP

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]

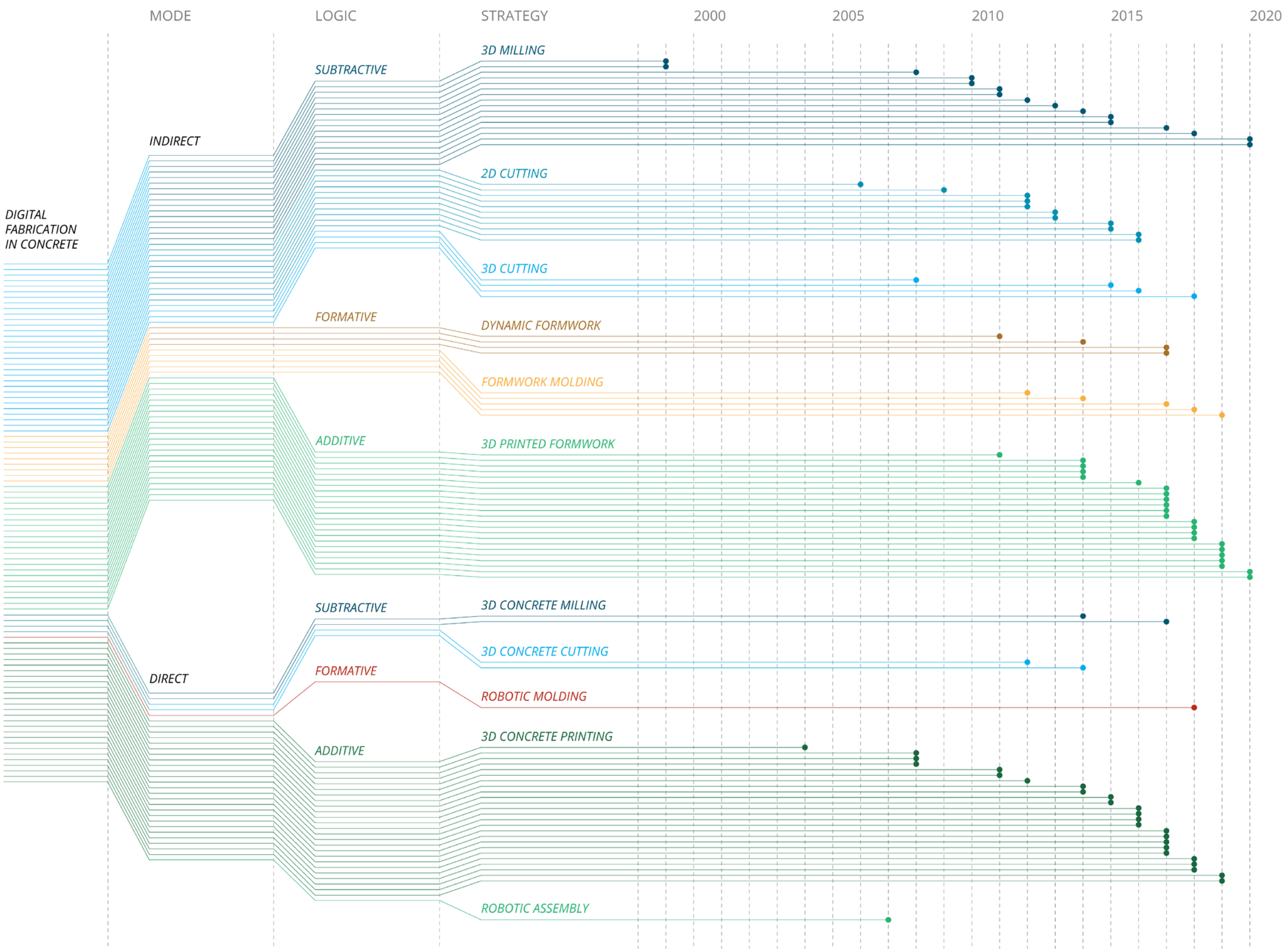
Although traditional concrete building technologies strategies still prevail, some digital processes have already been adopted into the construction industry, but many are also being developed through academic research. Independently of this status, today there are distinct digital fabrication processes 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.

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*

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



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

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

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

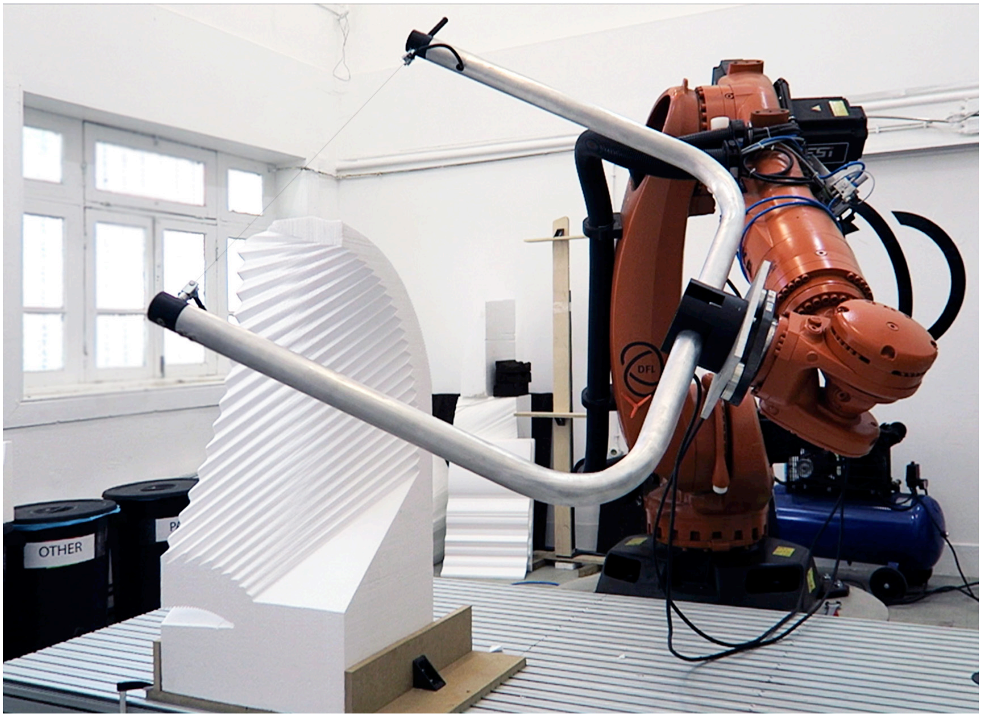
As such, given this background, it is relevant to explore solutions that balance their technical capability for automated construction and their design potential while simultaneously responding to contemporary environmental demands.

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

2 Robotic Hot Wire Cutting

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

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

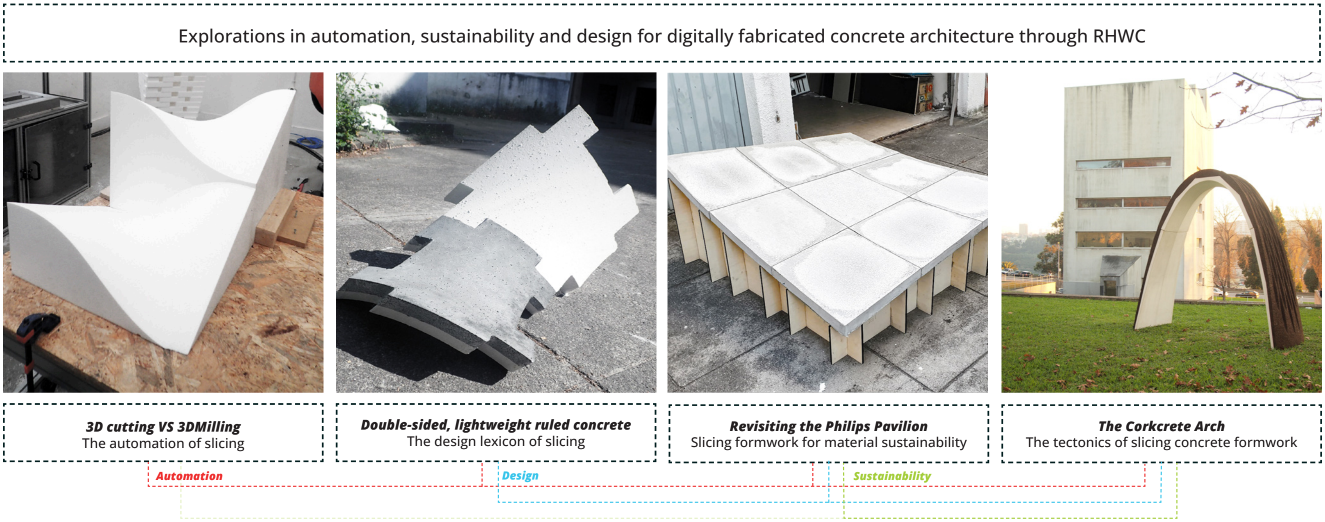


Thus, robotic hot wire cutting is a digital fabrication technology that employs this same slicing strategy, enhanced and adapted to the construction industry, by employing a hot wire end-effector attached to a multi-axis robotic arm (Figure 2). This drastically increases the freedom of movement and scale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

3 Exploring RHWC for Concrete Architecture: Four Experimental Prototypes

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

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



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

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

and material optimization of RHWC as well as the relation between design language, material and digital fabrication strategy. In the following sections, the findings from each experimental prototype are discussed and linked to the main issues raised.

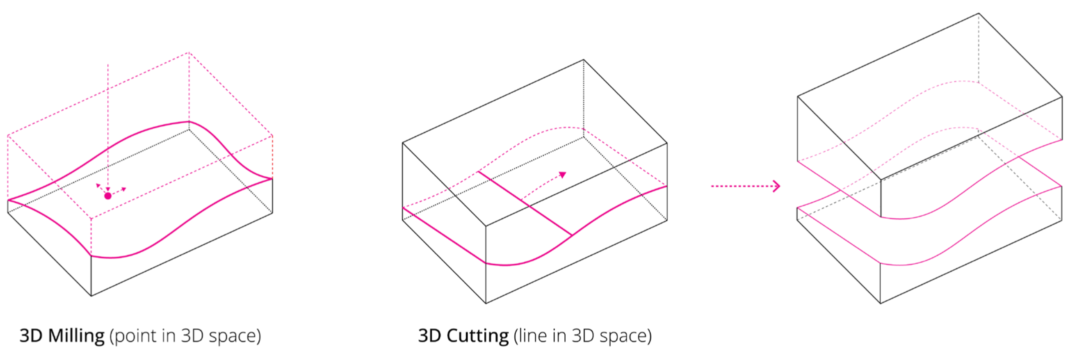
3.1 Automation in Slicing: 3D Cutting vs 3D Milling

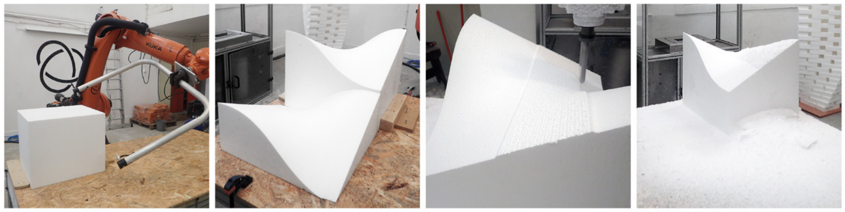
Automation is one of the cornerstones of the fourth industrial revolution in general but also in the specific case of the construction industry. In effect, it concerns the ability to produce architectural forms with increasing levels of complexity, precision and speed, directly from digital information,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

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

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

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





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

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

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

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

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

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

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

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

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

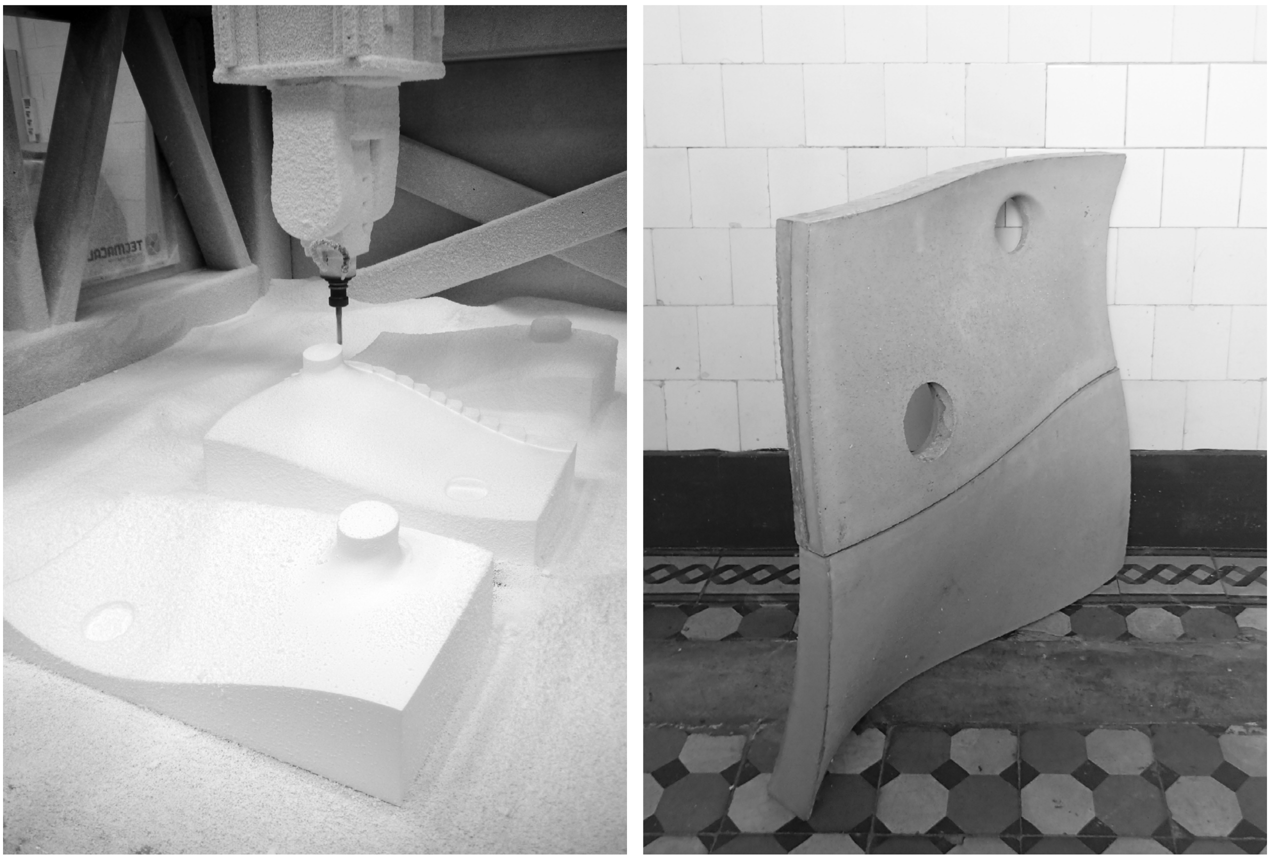


Fig. 6 Prototype A. 3D milled, customized concrete elements of variable double curved geometry (developed at DFL/CEAU/FAUP, in 2014, by the authors).

5 Alfonso Basterra, "Félix Candela y el borde libre. El caso de la capilla de Palmira de Cuernavaca," *Bitácora Arquitectura* 5 (2001): 38–47.

6 M. Bartoň, Helmut Pottmann and Johannes Wallner, "Detection and reconstruction of freeform sweeps," *Computer Graphics Forum*, vol. 33, no. 2 (2014): 23–32.

7 Pedro Martins, Paulo Campos, Nunes and Sousa, "Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting – Form, Texture and Composition," in *Real Time – Proceedings of the 33rd eCAADe Conference*, vol. 2 (Vienna: Vienna University of Technology, 2015), 341-351.

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

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

3.2 The Design Lexicon of Slicing

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

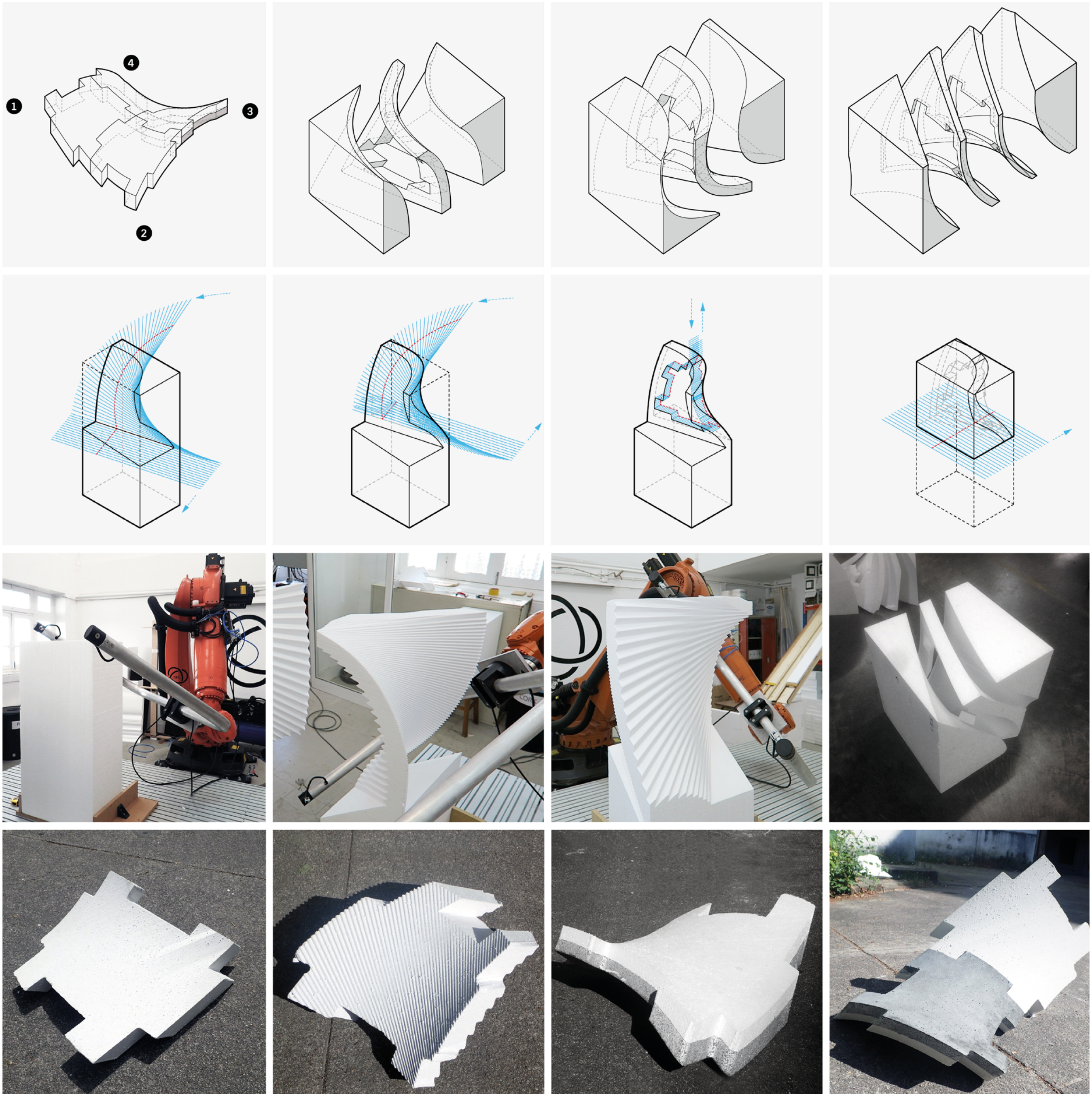
In general terms, a surface is ruled if through all of its points, at least one straight line can be passed that lies on the surface. Many particular ruled surfaces exist, from simpler ones such as the plane, the cylinder and the cone, to more complex ones such as the hyperboloid, the conoid, the hyperbolic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

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

Fig. 7 [opposite page] Prototype B: The MSE Panels; (top to bottom rows) a) panel geometry and layered mould design for panels 1, 2 and 3; b) cutting routine for panel 4 (front cut, back cut, perimeter cut, bottom cut); c) RHWC fabrication process and final mould for panel 1; d) finished parts showcasing textured surfaces, variable compositions and two assembled panels (developed at DFL/CEAU/FAUP, in 2015, by the authors).

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.


4
1
3
2

One of the main issues solved by this prototype was the particular geometry needed for the closed moulds necessary to actually cast concrete elements. While the issue of creating a general ruled surface in EPS was not difficult, as was demonstrated in Prototype A, the moulds for the interlocking geometry designed presented the added difficulty of creating an interior cavity with a jigsaw-like perimeter.

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

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

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

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

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

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

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

3.3 Sustainability Through Slicing

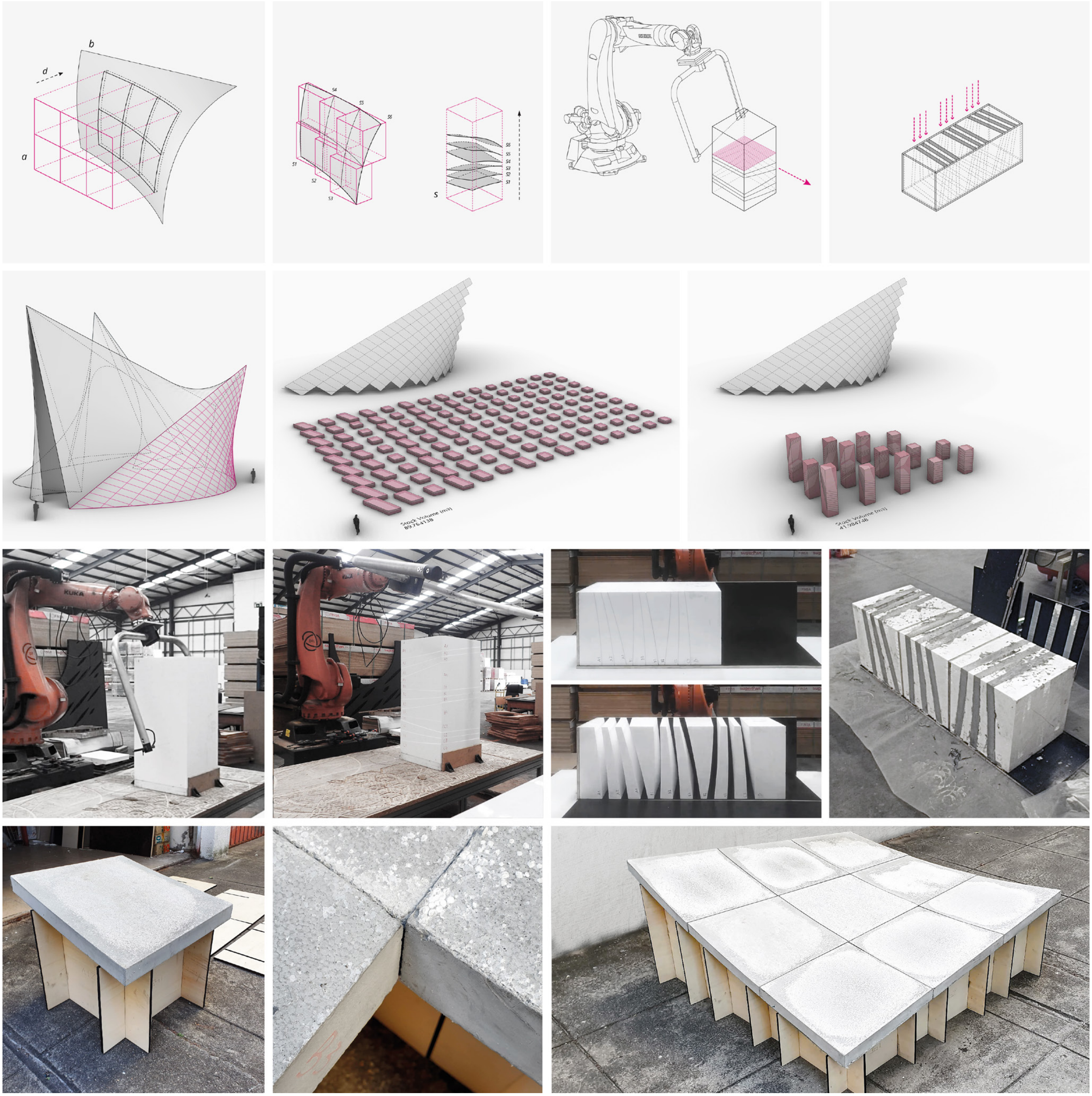
In addition to the actual production of cement, which is usually alluded to as one of the main sustainability issues in concrete construction, the production of formwork also represents a large part of costs, labour, material usage and energy expenditures in concrete building.[8] As such, optimizing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

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

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

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

9 Martins, Nunes, Campos and Sousa, "Rethinking the Philips Pavilion Through Robotic Hot Wire Cutting. An experimental prototype," in *Architecture in the Age of the 4th Industrial Revolution – Proceedings of the 37th eCAADe Conference*, vol. 3 (Porto: Faculty of Architecture University of Porto, 2019).


b
d
a
s
Stock Volume (m3)
89.764138
Stock Volume (m3)
41.984748

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.

side, like vertical shelves, if their boundary geometry is aligned throughout. In standardized solutions, this is used for flat panels, but with the use of RHWC and EPS moulds, several ruled slices can be performed sequentially in a large block of stock material, each defining a surface that can afterwards be separated and cast (Figure 8a).

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

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

All of the resulting panel geometries could then be automatically sorted and nested into stock EPS blocks in groups of 10 panels, resulting in 14 formwork stacks (Figure 8c). As an exercise, this subdivision and the corresponding layered mould strategy was compared again with the more traditional approach of 3D milling, where each panel requires one mould milled from its own stock block. Comparing material expenditures for both processes demonstrated that, while approximately 90 m³ 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 m². 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).

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

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

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

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

3.4 The Tectonics of Slicing Concrete Formwork

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

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

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

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

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

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

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

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

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

4 Balancing Design, Automation and Sustainability in Digital Making

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

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

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

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

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

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

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

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Marcela Noronha
Center for Studies on Innovation and Knowledge-Based Urban Development;
School of Civil Engineering, Architecture and Urban Design;
University of Campinas

Robson Canuto da Silva
Center for Studies on Innovation and Knowledge-Based Urban Development;
School of Civil Engineering, Architecture and Urban Design;
University of Campinas

Gabriela Celani
Center for Studies on Innovation and Knowledge-Based Urban Development;
School of Civil Engineering, Architecture and Urban Design;
University of Campinas

Placemaking in the Design of Knowledge-Based Urban Developments

Extending CIM Capabilities in the Planning Phase

Keywords
— Knowledge-based urban development (KBUD), placemaking, science parks, urban design, urban planning, city information modelling (CIM), public participatory geographic information systems (PPGIS)

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In this paper, we review the concept of science parks and their culmination as knowledge-based urban developments (KBUDS). Next, we describe the upgrading of second-generation science parks in urban fringes to knowledge territories based on the quintuple helix innovation model. This research aims to study planning and design tools that can be used to foster serendipity, vitality and high-quality living environments in otherwise sterile landscapes from a human point of view, as is generally the case in second-generation science parks. In this context, we discuss how city information modelling (CIM) capabilities can be extended with three placemaking aspects that are important to this type of development: social negotiation, urban vitality and legibility. Finally, we present the International Hub for Sustainable Development (HIDS), which is currently being planned in Campinas, Brazil, and some examples of the use of CIM in this project. We conclude that CIM can be used to increase public engagement in participatory processes by facilitating communication between stakeholders. In addition, it improves data collection in these processes and supports decision-making.

Introduction

In 1969, Peter Drucker stated "that knowledge has become the central 'factor of production' in an advanced, developed economy," using the term "knowledge economy" to describe this shift. For knowledge to be an economic driver it cannot be static, like the information contained in a book.[1] It must be dynamic and applied, generating technological innovation. "Knowledge, like electricity or money, is a form of energy that exists only when doing work."[2]

In 2000, the European Council, during a meeting in Lisbon, agreed to adopt "a new strategic goal for the Union in order to strengthen employment, economic reform and social cohesion as part of a knowledge-based economy," which confirmed an important change in the European economy that had already been underway since the last decades of the 20th century.[3]

Gerd Leonhard's famous allegory of the knowledge revolution illustrates this disruptive change, picturing the future as a non-male, non-white character, full of colours, shedding flowers and hearts, as opposed to a dull, white-collared white man with polluting chimneys coming out of his head. The image's title reads "Industrial & Mechanical x Digital & Exponential."[4] The image effectively conveys the shift observed by Yigitcanlar and Velibeyoglu "from industrial and mass production to knowledge-intensive goods and service production" economies, also referred to as knowledge-based economies.[5]

In cities, the knowledge economy concept was brought to fruition in science and technology parks. Also referred to as research parks or technopoles, they are used as a public policy to foster economic growth and urban development, and have been around since the 1950s.[6] According to Annerstedt, a science park is the result of an association between specialized professionals to foster a culture of innovation and knowledge exchange between its associates as well as increasing their competitiveness in a global market.[7] They usually result from the association between universities and research and development institutions. The most successful examples provide high-quality spaces and are equipped with "state-of-the-art telecommunications gear" in order to become more attractive to workers and users. These associations are usually set in a space in which the associates are close to each other. While this spatial element should not limit knowledge exchange, the availability of specialized infrastructure, services and equipment can be increased by it.[8]

Science and technology parks have, however, evolved and changed with the knowledge revolution. The author classifies these parks into three different generations: a) the first were developed on university campuses aiming at directly applying research results to generate economic opportunities for the host institutions; b) the second are those created and managed by the private sector and are usually located on urban fringes;

1 Peter F. Drucker "The Knowledge Economy," in *The Age of Discontinuity: Guidelines to Our Changing Society,* ed. Peter F Drucker (Oxford: Butterworth-Heinemann, 1969), 248, https://doi.org/https://doi.org/10.1016/B978-0-434-90395-5.50016-X.
2 Ibid., 252.
3 European Council, "Lisbon European Council 23 and 24 March 2000 Presidency Conclusions." Lisbon, 2000.
4 Gerd Leonhard, "The Future of Knowledge," *Inside Learning Technologies & Skills* (December 2013): 7-8.
5 Tan Yigitcanlar and Koray Velibeyoglu,"Knowledge-Based Urban Development: The Local Economic Development Path of Brisbane, Australia," *Local Economy 23,* no. 3 (August 2008): 196, https://doi.org/10.1080/02690940802197358.
6 Laura Lecluyse, Mirjam Knockaert and André Spithoven, "The Contribution of Science Parks: A Literature Review and Future Research Agenda," *The Journal of Technology Transfer* 44, no. 2 (April 19, 2019): 559–595, https://doi.org/10.1007/s10961-018-09712-x.
7 Jan Annerstedt, "Science Parks and High-Tech Clustering," in *International Handbook on Industrial Policy*, ed. Patrizio Bianchi and Sandrine Labory (Cheltenham: Edward Elgar Publishing, 2006), 279–97.
8 Ibid.

9 Ibid.
10 Adam Hayes, Toby Walters and Amanda Jackson, "What Is the Knowledge Economy? Definition, Criteria, and Example," Investopedia, 2021, https://www.investopedia.com/terms/k/knowledge-economy.asp.

and c) the third generation, aimed at fostering feedback-based innovation between research and business sectors, involving universities, private sectors and local government, are typically located in urban centres.[9]

As the different models of innovation evolved, some older science parks had to adapt to include new functions such as housing, cultural centres and a living environment. This adaptation is especially needed in the case of second-generation parks, that do not adhere to contemporary urbanism concepts such as compacity, diversity, walkability, etc. This is a recurring problem that must be tackled. Furthermore, since these areas are typically located in urban fringes, their densification is challenging from the environmental point of view. This is a complex transformation that requires interdisciplinary collaboration and specific planning and design tools.

This paper is part of a larger ongoing research on the concept of science parks in the wake of the knowledge revolution. We propose a fourth generation of science and technology areas which results from the upgrading of second-generation suburban science parks. It applies the quintuple helix innovation model as a paradigm to develop sustainable knowledge hubs as living laboratories, with living areas and high-quality daily life. However, achieving the required serendipity and vitality through urban planning alone is no trivial matter. Our aim is to discuss how to create welcoming environments with their catalytic role in the development of a sustainable life in this evermore common challenge.

We begin by reviewing concepts such as the knowledge economy and the helix models of innovation. Next, we review three generations of science parks and propose a fourth. We illustrate the concept of urban fringe KBUDs with an example in Paris, France. In addition, we discuss how this concept is being applied in the development of the International Hub for Sustainable Development (HIDS) in Campinas, Brazil. Finally, we present preliminary studies that will be further implemented through city information modelling (CIM) to contribute to placemaking: public participation, urban vitality metrics and landmark placement for legibility.

From the Knowledge Economy to the Quintuple Helix Innovation Model

The knowledge economy is defined by INVESTOPEDIA as "a system of consumption and production that is based on intellectual capital. It refers to the ability to capitalize on scientific discoveries and applied research." It corresponds to "a large share of the activity in most highly developed economies" and is based on "intangible assets such as the value of its workers' knowledge or intellectual property."[10]

A knowledge-based economy is the result of a broader contemporary phenomenon, the knowledge society, which is defined by UNESCO's International Bureau of Education as a society that is able to "identify, produce, process, transform, disseminate and use information to build and apply knowledge for human development."[11] This type of evolved society is also associated with plurality, inclusion, solidarity, and participation.[12]

In the 1990s, Etzkowitz and Leydesdorff realized how the roles of universities, companies and government were changing in different countries in the emerging knowledge society:

> In some countries with a laissez faire capitalist tradition such as the U.S. government is playing a greater role in innovation in the civilian economy (Etzkowitz 1994a) while in former socialist societies government has withdrawn from its previous position of total control of science and technology policy; adopting a stance more in accord with laissez faire principles. Multi-national institutions such as the European Union, the World Bank and the U.N. are also moving to embrace concepts of knowledge based economic development that bring the knowledge, productive and regulatory spheres of society into new configurations. In this conference, we wish to study the role of the sciences in this changing environment with a focus on the university's position in the newly emerging knowledge infrastructure.[13]

They called this academic–industry–government relation a "triple helix." It was largely illustrated by graphics that show three overlapping circles, with the different levels of interactions between the actors represented by the larger or smaller intersection areas. Later on, Carayannis and Campbell extended the model to a quadruple helix to include communication with civil society, via all forms of media, in order to obtain public support for innovation policies:

> The 'Quadruple Helix' emphasises the importance of also integrating the perspective of the media-based and culture-based public. What results is an emerging fractal knowledge and innovation ecosystem, well-configured for the knowledge economy and society.[14]

In a later paper, the same authors extended this model to a quintuple helix to include the perspective of the 'natural environments of society':

> Within the framework of the Quintuple Helix innovation model, the natural environments of society and the economy also should be seen as drivers for knowledge production and innovation, therefore defining opportunities for the knowledge economy. (…) The Quintuple Helix supports here the formation of a win-win situation between ecology, knowledge and innovation, creating synergies between economy, society, and democracy.

11 IBE-UNESCO, "Knowledge Society," *Glossary of Curriculum-Related Terminology* (International Bureau of Education UNESCO, 2013), 35.
12 Jérôme Bindé, *Towards Knowledge Societies* (Paris: UNESCO, 2005).
13 Henry Etzkowitz and Loet Leydesdorff, "The Triple Helix – University-Industry-Government Relations: A Laboratory for Knowledge Based Economic Development," *EASST Review* 14, no. 1 (1995): 14.
14 Elias G. Carayannis and David F J Campbell,"'Mode 3' and 'Quadruple Helix': Toward a 21st Century Fractal Innovation Ecosystem," *International Journal of Technology Management* 46, no. 3–4 (2009): 201.

> Global warming represents an area of ecological concern, to which the Quintuple Helix innovation model can be applied with greater potential.[15]

In other words, in the quintuple helix model, the environment is not only seen as an ecological concern, but also as a business opportunity and a potential driver of development. Taking into consideration a wider scale, the shift towards a knowledge-based or 'post-industrial' economy should be seen in conjunction with the emergence of 'newly industrialized countries' and the new global divisions of labour.[16] We must, therefore, ask ourselves if a community that profits from intellectual activities and delegates extraction of natural resources and industrial production to other parts of the country or of the world (especially those with cheap labour) can in fact be considered sustainable. For this reason, we stress the importance of a knowledge-based society and economy in contributing to the sustainable development of not only their own community, but of the world in general.

Four Generations of Science and Technology Parks and Districts

As previously stated, Annerstedt describes three generations of science parks. He associates them with three styles of innovation: science push (in which innovations created at the university are offered to the industry), market pull (in which the industry asks for specific developments by universities) and interactive or feedback-based.[17] In the following subsection, we analyse, compare, and exemplify these three generations and propose a fourth. The latter is illustrated with an existing example in the second subsection.

Comparative Analyses of the Four Generations of Science and Technology Parks and Districts

According to Annerstedt, the first generation of science parks aimed to create economic opportunities for universities by applying their research results. For that reason, these parks were typically created by the universities themselves, usually next to or inside their campuses.[18] One of the first examples was Stanford Research Park, created in the early 1950s.

The second generation of parks aimed to "create technologies suitable for economic utilization and encourage university students to become entrepreneurs."[19] These were usually created by business organizations and managed by the private sector and were not necessarily located close to universities, but also not in city centres. An example of second-generation parks is Sophia Antipolis Technopole, created in the 1970s in southern France.

Third-generation parks were based on the interactive or feedback-based innovation model, were typically located in "bustling city centres" and were usually created by universities, businesses and the local

15 Carayannis, Thorsten D Barth, and Campbell, "The Quintuple Helix Innovation Model: Global Warming as a Challenge and Driver for Innovation," *Journal of Innovation and Entrepreneurship* 1, no. 1 (2012): 1 https://doi.org/10.1186/2192-5372-1-2.

16 Martin Sokol, "The 'Knowledge Economy': A Critical View," in *Regional Economies as Knowledge Laboratories,* ed. Philip Cooke and Piccaluga Andrea (Cheltenham: Edward Elgar Publishing, 2005), 272, https://doi.org/10.4337/9781845423391.00019

17 Annerstedt, "Science Parks."

18 Ibid.

19 János Gyurkovics and Miklós Lukovics, "Generations of Science Parks in the Light of Responsible Innovation," in *Responsible Innovation,* ed. János Gyurkovics and Miklós Lukovics (Szeged: University of Szeged, Faculty of Economics and Business Administration, 2014), 199.

government together. Feedback-based innovation results from the "cooperation between economic, academic and government players and the place of operation of organizations participating in global and regional innovation activities," and its aim is to "improve the welfare of the local community, through supporting efficient cooperation between the above mentioned three types of players," "contribute to the development of their regions' entrepreneurial culture and establish two-way communication between the creators and users of knowledge and technologies."[20] The third generation can thus be associated with the quadruple helix model, which includes society as a key factor. A good example of this type of environment is 22@, which is not exactly a science park, but rather a large urban renovation project located in Barcelona's Poblenou district, with the same aims. Barcelona was one of the first European cities to implement a plan to deliberately move from the industry-based economy to the knowledge-based. Since the early 2000s, this formerly industrial area (22@) was converted into a "platform for the knowledge economy and society" using heavy investments in infrastructure, mobility, housing (including social housing), cultural centres, green areas, universities and buildings for science, technology and business activities.[21] The idea was to attract a new class of talented and highly skilled workers to a neighbourhood that was full of empty, outdated, abandoned industrial plants.

We can extend Annerstedt's and Gyurkovics and Lukovics' proposal with a fourth generation of science and technology areas that corresponds to Carayannis, Barth & Campbell's quintuple helix innovation model, including the environment both as an ideological concern and a driver of development.[22] As in the third generation, this one is not exactly a park, but rather an urban district, and it has been called a knowledge-based urban development (KBUD). A KBUD is defined by the IGI-Global dictionary as:

> The new development paradigm of the knowledge economy era that aims to bring economic prosperity, environmental sustainability, a just socio-spatial order and good governance to cities and produces a city purposefully designed to encourage the production and circulation of knowledge in an environmentally conserved, economically secure, socially just and well-governed human setting, a knowledge city.[23]

The term was coined by Yigitcanlar, who has also published several papers in which he proposes different frameworks for these areas.[24] As in the quintuple helix model, KBUD framework diagrams include the natural environment and sustainability as key factors, by means of word combinations such as "environmental sustainability," "sustainable development," "sustainable urban development," "environmental and

20 Ibid., 198–99.
21 Josep M. Piqué, "Knowledge Cities on Smart Cities: 22@Barcelona Case," *Encontro Nacional Da Indústria Da Construção* (Rio de Janeiro: CBIC, 2019).
22 Annerstedt, "Science Parks"; Gyurkovics and Lukovics, "Generations of Science Parks"; Carayannis, Barth, and Campbell, "Quintuple Helix Innovation Model."
23 Yigitcanlar, "Knowledge-Based Urban Development," in *Encyclopedia of Information Science and Technology*, ed. D.B.A. Mehdi Khosrow-Pour, 3rd ed. (Hersey, PA: IGI Global, 2015), 7475–7485.
24 Yigitcanlar et al., "Understanding 'Smart Cities': Intertwining Development Drivers with Desired Outcomes in a Multidimensional Framework," *Cities* 81 (November 1, 2018): 145–60, https://doi.org/10.1016/j.cities.2018.04.003; Nimish Biloria, "From Smart to Empathic Cities," *Frontiers of Architectural Research* 10, no. 1 (March 2021): 3–16, https://doi.org/10.1016/j.foar.2020.10.001; D L Chang et al., "Knowledge-Based, Smart and Sustainable Cities: A Provocation for a Conceptual Framework," *Journal of Open Innovation: Technology, Market, and Complexity* 4, no. 1 (December 13, 2018): 5, https://doi.org/10.1186/s40852-018-0087-2; S Teriman, T Yigitcanlar, and S Mayere, "Sustainable Urban Development: An Integrated Framework for Urban Planning and Development," in *Rethinking Sustainable Development: Urban Management, Engineering, and Design.*, ed. T Yigitcanlar (United States: IGI Global, 2010), 1–14, https://doi.org/10.4018/978-1-61692-022-7.ch001; T Yigitcanlar, K Velibeyoglu, and S Baum, *Knowledge-Based Urban Development: Planning and Applications in the Information Era*, ed. T Yigitcanlar, K Velibeyoglu, and S Baum, Premier Reference Source (Information Science Reference, 2008).

Fig. 1 The four generations of science and technology parks with their respective innovation models with examples, December 2021 (by authors).

developmental challenges," "sustainability capacity," "sustainable urban infrastructure," "enviro-urban", etc. These are not just related to the "quality of life and place" which is needed for attracting and retaining talents, but also as a source of innovative—and profitable—businesses that are needed more than ever in a world of climate change and ecological disaster.

Fourth-generation science and technology urban developments, proposed herein, can be defined as *KBUD*s located on the outskirts of cities, where there is an opportunity to apply the latest technologies to obtain a proper coexistence between human activities and the natural environment. A good example of this type of area is the *Établissement Publique d'Aménagement Paris-Saclay* (EPA Paris-Saclay), also known as *Campus Urbain*. A summary of the four generations of science parks and districts, their respective innovation models, and examples of each can be seen in Figure 1.

EPA Paris-Saclay: A Fourth-Generation Science Park

Launched in 2010 and located south of Paris, EPA Paris-Saclay aims to "Develop a centre of scientific and technological excellence in a sustainable and pleasant area to live in," as stated on its home page.[25] It comprises three different zones, two of which have already been labelled *éco-quartiers,* a definition created by the French government in 2012.[26]

The EPA Paris-Saclay operation consisted in creating a new mixed zone to connect some of these anchors, following sustainable urbanism principles such as compactness, mixed-use, social diversity, sustainable mobility, energy efficiency and soil permeability.[27] This took place in a suburban territory (the plateau of Saclay), which had been sparsely

25 Ministère logement habitat durable, "Les Écoquartiers," https://umap.openstreetmap.fr/en/map/les-ecoquartiers_116165#14/48.7058/2.1428; "EPA Paris-Saclay," 2022, https://epa-paris-saclay.fr/.

26 Ministère de l'Egalité des territoires et du Logement, "Dossier de Presse: Lancement du Label National ÉcoQuartier" (Brétigny-sur-Orge, 2012).

27 EPA Paris-Saclay, "Paris-Saclay, une opération urbaine pour un cluster scientifique et industriel," Plateau de Saclay, 2015, https://epa-paris-saclay.fr/; EPA Paris-Saclay, "Le Projet urbain de moulon," Plateau de Saclay, 2014, https://epa-paris-saclay.fr/

occupied by academic institutions and private and public research centres (but no residential or commercial areas) for more than 50 years. The project comprises state-of-the-art environmental solutions, such as neighbourhood heating and cooling, which includes the reuse of waste heating from the IDRIS supercomputer Jean Zay and nature-based solutions for stormwater mitigation and managed aquifer recharge.[28] Moreover, as a result of a partnership with the association Terre et Cité, a natural and agricultural zone was established by law in 2010 on the plateau, guaranteeing the preservation of forests and traditional cultivation areas, and thus of water sources and the local biodiversity.[29] This partnership also resulted in the Manger Local programme, which fosters the consumption and valorization of local produce, circular economy and environmental education and consciousness, through an online platform that connects consumers to producers.[30]

The EPA Paris-Saclay is full of examples of the use of online digital technologies for gathering and distributing georeferenced information for inhabitants and visitors. This is important for creating a sense of community in this artificially developed urban environment, something that has also been called digital placemaking.[31] The *Carte Ouverte* platform, shown in Figure 2, is a good example of a tool they developed for sharing from cultural events to visitable heritage and locally grown produce.[32]

However, the Paris-Saclay project is not free of criticism, especially regarding social negotiation.[33] Moreover, once the first inhabitants moved in, the EPA Paris-Saclay had to create a special programme for urban activation, aiming to “encourage neighbourhood life, collective initiatives, and the mixing of audiences” and supporting “the appropriation of a new neighbourhood and to create the conditions conducive to the development of an urban life”, as stated on its “Activation” webpage.[34]

We hypothesize that city information modelling (CIM) could be used as a placemaking tool during the design phase of this type of urban development in order to help create a more active territory.

28 Yoann Verger et al., “A N, P, C, and Water Flows Metabolism Study in a Peri-Urban Territory in France: The Case-Study of the Saclay Plateau,” *Resources, Conservation and Recycling* 137 (October 2018): 200–213, https://doi.org/10.1016/j.resconrec.2018.06.007; Rafael Medeiros, “Reuse by the Paris-Saclay District Heating and Cooling Network of the Waste Heat from the IDRIS Supercomputer Jean Zay” (Paris: PRACE Session on Infrastructures, 2021).

29 Terre & Cité, “Protéger Les Terres Agricoles,” Plateau de Saclay, 2017, https://terreetcite.org/proteger-les-terres-agricoles/; EPA Paris-Saclay, “Zone de Protection Naturelle, Agricole et Forestière Du Plateau de Saclay,” Plateau de Saclay, 2018, https://epa-paris-saclay.fr/

30 Camille Tedesco et al., “Potential for Recoupling Production and Consumption in Peri-Urban Territories: The Case-Study of the Saclay Plateau near Paris, France,” *Food Policy* 69 (May 2017): 35–45, https://doi.org/10.1016/j.foodpol.2017.03.006

31 Jordan Frith and Jacob Richter, “Building Participatory Counternarratives: Pedagogical Interventions through Digital Placemaking,” *Convergence: The International Journal of Research into New Media Technologies* 27, no. 3 (June 12, 2021): 696–710, https://doi.org/10.1177/1354856521991956

32 Dorian Spaak, Léa Marzloff and Sabine Chardonnet-Darmaillacq, “Carte-ouverte du Plateau de Saclay,” http://www.saclay.carte-ouverte.org/#

33 Hervé Brédif, “Quel projet d’intérêt national pour le Plateau de Saclay ?” *L’Espace Géographique* vol. 38, no. 3 (September 11, 2009): 251–66, https://doi.org/10.3917/eg.383.0251

34 Paris-Saclay Version Beta, “L’activation du campus urbain, sur les communes de Gif-Sur-Yvette, Orsay et Palaiseau,” https://beta.epaps.fr/activation/

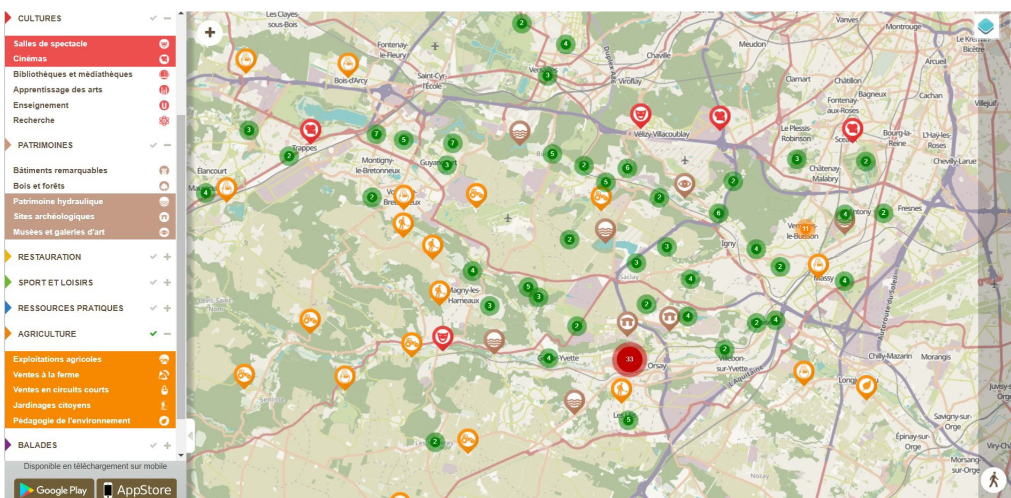


Fig. 2 The online interface of the *Carte Ouverte* platform, December 2022, (Dorian Spaak, Léa Marzloff and Sabine Chardonnet-Darmaillacq).

From Campinas High-Technology Pole to the International Hub for Sustainable Development (HIDS)

The city of Campinas, in a metropolitan area of 2 million inhabitants, 100 km north of São Paulo, plans to convert a former 2nd-generation science and technology park from the 1980s into a 4th generation knowledge-based urban development. The former Campinas High Technology Pole, approximately 11 km2, was originally created in the 1980s as an urban expansion designated as a strategic hub for the development of the city, envisioned as the future Brazilian Silicon Valley. However, over the past decades most of its land was left underdeveloped due to real estate speculation, lack of public investment in infrastructure, and urban regulation restrictions, which made the construction of residential and commercial areas unfeasible. In 2014, the University of Campinas (UNICAMP), a public research university, acquired a large parcel of land (still with agricultural use) adjacent to its suburban campus, located in the Campinas High Technology Pole. The original idea was simply to use the new land to expand the University's first-generation Science Park that was already located on its campus. However, soon it became clear that by owning this land the university could induce the transformation of the entire pole into a fourth-generation KBUD. Thus, the idea of the International Hub for Sustainable Development (HIDS) emerged.

In addition to UNICAMP's campus, the pole includes two other higher education institutions, public and private research and development centres, two hospitals and the largest and most modern synchrotron particle accelerator in the southern hemisphere. More recently, an international school was also installed in the area. The morphological characteristics of the site include flooding plains, springs and streams, natural forest patches that need to be connected through ecological corridors, according to the present law, and historic heritage sites. The need to reconcile the preservation of this natural and architectural patrimony with the potential for the urban and economic development of the region makes the new planning of the area a challenge.

Approximately half of the HIDS' area, 272 hectares, remains unoccupied, out of which 101.3 hectares are in the parcel acquired by UNICAMP. Another 170.9 hectares are private lands that, despite being empty, belong to owners who have expressed their intention to build gated communities, which could jeopardize the project by decreasing the area's regional connectivity. This complex scenario makes it imperative to develop policies and incentives for sustainable development in this region in order to make the best possible use of this unique concentration of science and technology infrastructure.

In March 2020, an agreement was established between UNICAMP, Campinas Municipal Government and the Inter-American Development Bank (IDB) for the development of a master plan for HIDS, which included multiple consultancies (on natural heritage, on business models and on

35 KRIHS, "HIDS Principles and Design Scenarios: Consultancy for Developing the Physical and Spatial Plan for Campinas" (Campinas, Brazil, 2022).

legal framework) as well as a preliminary urban plan designed by the Korean Research Institute for Human Settlement (KRIHS). After a series of workshops, the business model consultancy, a joint venture between *Sociedade Portuguesa de Inovação* (SPI) and International Association of Science Parks and Areas of Innovation (IASP), identified some vocations for the area, such as ICT, health and agricultural technologies, in addition to the opportunity for developing sustainable urban technology businesses in a living laboratory environment.

KRIHS' methodology for the development of the urban plan was based on multiple cycles of meetings and workshops with the project's stakeholders to define the visions, principles and strategies, and to discuss three possible scenarios before presenting a final proposal. KRIHS' design principles and strategies were based on new urbanism and transport-oriented development (DOT) concepts, such as urban density and compactness, diversity of uses, promotion of active mobility for short journeys and public transport for longer journeys.

In this context, the company adopted six main strategies for HIDS' urban plan: 1) create a nucleus that brings together innovation activities, businesses and development, and research centres to trigger the development of the area; 2) use the urban design of streets and blocks to encourage interaction and communication; 3) connect the HIDS road network with the surrounding roads; 4) consider the existing division between the plots for the implementation of the road network and land occupation; 5) emphasize the boundaries between public and private areas; 6) preserve the natural ecosystem through two different types of green spaces, the active ones (parks, paths and squares) and the passive ones (environmental preservation areas).[35]

The proposal provides for the perimeter occupation of blocks with an intermediate density in residential areas, with 10- to 15-storey apartment buildings with an average of 300 people/ha. Mixed use is advocated within buildings with a uniform division between residential, commercial and service uses, social housing and community facilities. For the other types of use, 5- to 7-storey buildings are proposed with floor-to-area ratios (FAR) between 2 and 3.

In order to promote active mobility, multifunctional streets of different hierarchies are proposed, with the location of shops, anchor facilities and public spaces on the ground floors of the buildings that combine a design oriented towards the integration between streets and blocks. Within the HIDS area, personal mobility is promoted, with the use of bicycles and other devices shared through mobile applications, while public transport will be prioritized to connect the site to other regions of the city through bus rapid transit lines. Connection with existing roads was prioritized to achieve a higher level of connectivity between HIDS and its surroundings.

The master plan developed by KRIHS contains of most of the premises of new urbanism, but this may not suffice to ensure the implementation of the quintuple helix model of innovation. The planning phase should allow for simulations that go beyond floor to area ratios and land-use distribution. Moreover, these new districts are often artificially and quickly created and lack identity and sense of belonging. There are subjective qualities that influence placemaking success and could be incorporated in the process to assure better urban quality.

HIDS as an Opportunity for Applying City Information Modelling

Traditional scenario-building methods are typically difficult to update and adjust in a collaborative and participatory process. Computational scenario-building and participatory tools allow manipulation of indexes, showing multiple alternatives and their outcomes and consequences. Moreover, being online they are easily editable and allow a greater number of local citizens to be reached, overcoming the limitations of traditional participation methods such as those described by Moughtin et al. based on static models.[36] The author, citing Gibson, points out that "nothing is more destructive of participation" than finished scale models, as people are intimidated to make changes to something that looks ready for presentation.[37] Thus, giving participants the opportunity to manipulate parameters and interact with an online urban scenario with the click of a mouse, to see the possible outcomes, can empower them in this process.

This type of participation is called participatory modelling and is defined as an "approach in which stakeholders from different domains come together for problem formulation and description, input collection, problem-solving, continuous validation, and finally decision-making."[38] For Singh, Baalsrud Hauge, and Wiktorsson, the ubiquity of computational methods in different fields of applied sciences is making computer-based simulation evermore present in the process. It enables the use of participatory modelling for quantitative and empirical purposes, leading to what they call simulation-based participatory modelling.[39] It has been used for different purposes in literature: to facilitate the communication and conflict resolution between different stakeholders; to support decision-making, and for knowledge integration and generation. More recently, it has evolved into empirical participatory modelling and is being used for the development and validation of computational and mathematical abstractions of existing scenarios and used to optimize systems and produce quantitative data to aid decision-making.[40] The aim of using simulation-based participatory modelling in a project is to collect data and process it using different methods and output results and presentation material to guide decision-making.

Data collection is often done using analogical methods such as focus groups, interviews, workshops, and surveys, that can potentially be

36 Cliff Moughtin et al., *Urban Design: Method and Techniques*, 2nd ed. (London: Routledge, 2012), https://doi.org/10.4324/9780080520254.
37 Ibid.; Tony Gibson, *People Power: Community and Work Groups in Action* (Harmondsworth, New York: Penguin, 1979).
38 Amita Singh, Jannicke Baalsrud Hauge, and Magnus Wiktorsson, "Simulation-Based Participatory Modelling in Urban and Production Logistics: A Review on Advances and Trends," *Sustainability* 14, no. 1 (December 21, 2021): 1, https://doi.org/10.3390/su14010017
39 Ibid.
40 Singh, Baalsrud Hauge, and Wiktorsson, "Simulation-Based Participatory Modelling," 8.

enhanced using computational systems, such as online questionnaires, word clouds generators, etc. However, for crowdsourcing information, public participatory geographic information systems (PPGIS) are more commonly employed.[41] For data processing, empirical modelling and presentation, city information modelling (CIM) can be used with inputs collected using PPGIS.

In the following subsection, we discuss CIM and its integration with PPGIS. In the next, we present and discuss three preliminary studies carried out for the purpose of implementing simulation-based participatory modelling in the HIDS project. The first was developed with the purpose of using parametric modelling in conjunction with PPGIS to crowdsource public input on different design scenarios. The second is an indicator to quantitatively evaluate vitality in design scenarios which can be implemented in a PPGIS software to aid communication, decision-making, and policy development. The last is a parametric empirical model, applying Space Syntax, with the purpose of supporting design decisions by evaluating scenarios on their legibility. It can be used to develop scenarios based on crowdsourced data using CIM–PPGIS, similarly to the first study.

City Information Modelling

Originally, city information modelling (CIM) was introduced as an extension of building information modelling for the urban environment, which can be understood as semantically enriched three-dimensional city models integrated with geographic information systems (GIS).[42] In other words, CIM can be used to extend GIS for applications at a smaller scale, i.e., for urban design. In a more recent review, Gil identified other types of applications for this technology that go beyond geometric and semantic aspects.[43] In combination with parametric, generative, and data-driven methods, CIM can be used to create possible scenarios and evaluate them based on objective information to inform policy and spatial planning decisions through the observation of existing phenomena and extrapolation of data.[44]

By using spatial and GIS data as inputs, CIM can be used for simulation-based participatory modelling as several GIS applications have also incorporated participatory tools to collect information volunteered by the public. As mentioned above, these tools are known as public participatory GIS (PPGIS) and can be used to crowdsource information that associates people's opinions, personal knowledge, "perceptions and emotions" with the territory.[45]

The main drawback of using PPGIS in participatory processes is its overreliance on the population's access to digital and connected technology, which, on the level of the individual citizen, can be a problem. Depending on the population to be engaged in the participatory process, this can be offset by using simpler web applications that are also accessible on smartphones. In contrast, the main advantage in the use of PPGIS is the potential to engage a larger population.[46] As noted by Haklay, Jankowski and Zwoliński, most

41 Ibid., 9.
42 Arivaldo Leão de Amorim, "Discutindo City Information Modeling (CIM) e conceitos correlatos," *Gestão & Tecnologia de Projetos* 10, no. 2 (November 6, 2015): 87, https://doi.org/10.11606/gtp.v10i2.103163
43 Jorge Gil, "City Information Modelling: A Conceptual Framework for Research and Practice in Digital Urban Planning," *Built Environment* 46, no. 4 (2020): 501–27, https://doi.org/10.2148/BENV.46.4.501
44 Tom Verebes, *Masterplanning the Adaptive City: Computational Urbanism in the Twenty-First Century* (New York: Routledge, 2013); Jorge Gil, "City Information Modelling: Framework."
45 Muki Haklay, Piotr Jankowski, and Zbigniew Zwoliński, "Selected Modern Methods and Tools for Public Participation in Urban Planning – A Review," *Quaestiones Geographicae* 37, no. 3 (September 1, 2018): 128, https://doi.org/10.2478/quageo-2018-0030
46 Ibid., 130.

people that attend public participation meetings do so because they have a negative opinion of a project and thus feel compelled to participate.[47] Therefore, PPGIS and CIM for the purposes of visualization, communication, empirical modelling and scenario testing employing a variety of methods, including web-based applications, can increase public participation by facilitating the engagement of people that do not have the option or drive to participate in person in workshops and open meetings. Wider participation generates a higher data volume and yields more reliable and significant results for the participatory processes.

In the case of HIDS specifically, and in other areas subject to real estate speculation and gentrification, the use of PPGIS with CIM for scenario building and economic evaluation has the potential to help convince developers to adopt alternative models to those commonly used in peri-urban areas, such as gated communities, which is not in line with the KBUD principles. Furthermore, information and communication technology (ICT) opens an opportunity for digital placemaking, i.e., in order to promote public participation, collaboration in the design process, and a sense of belonging to the place.[48]

Gil lists a number of concepts that have been successfully incorporated into CIM and cites the integration of parametric, generative and procedural modelling with geoprocessing and spatial analyses in the urban planning and design processes.[49] He expands this definition by relating CIM to smart cities:

> City information modelling is the practice of using interactive digital technologies in the process of urban planning, by all actors and stakeholders, to collaboratively deliver the vision of a smart city: a sustainable, inclusive, healthy, prosperous and participative city. CIM consists of an ecosystem of interoperable (open source) tools from different knowledge domains, for data processing, urban analysis, design, modelling, simulation and visualization.[50]

To achieve this broader scope, beyond PPGIS and CIM, opportunities for wider public and stakeholder participation must be created, such as digital placemaking. Halegoua calls for urban planners, developers and designers to "recognize and cultivate" the bond between people and places.[51] The specific qualities and the "character of places" should be evident in the design to inspire affection instead of awe, in order to become stimulating and lively instead of simply convenient or efficient. Thus, "developers need to consider the cultural aspects of intended innovation from the outset, not as an afterthought," focusing on factors such as legibility, local characteristics (environmental, climatic), human behaviour and cultural values.[52] This can be achieved by utilizing social media and ICT to promote the development, holding scientific communication events, maintaining a transparent planning process, hosting artistic exhibitions, performances,

47 Ibid., 128.
48 Germaine R Halegoua, *The Digital City, Media and the Social Production of Place* (New York: New York University Press, 2020), https://doi.org/doi:10.18574/nyu/9781479839216.001.0001
49 Gil, "City Information Modelling: Framework."
50 Ibid., 512.
51 Halegoua, *The Digital City,* 63–64.
52 Ibid., 65.

using PPGIS to engage public participation in planning decisions, attracting the public to activities to digitally map culturally important places and view sights, local knowledge, public memory and folklore, and general wants and needs. Furthermore, digital placemaking can be used pedagogically to continually instil a sense of place and belonging through continued efforts long after the development is implemented.[53]

However, not all the concepts related to the specific characteristics that we seek in urban fringe KBUDS are discussed by these authors. In the case of HIDS, the master plan is not enough to ensure that the required urban vitality is achieved. The HIDS project represents a unique opportunity for applying CIM to simulate different scenarios and the resulting levels of vitality. For this aim, we need to identify the proper vitality indicators and their effect on the area.

These disciplines have traditionally been heavily reliant on written plans, codes, manuals, textual rules and mapped zoning regulations that can be challenging to translate into computer programs and may lack sufficient information. The activities that do rely heavily on programming are analytical and usually apply geographic information systems (GIS) software, meaning geometric data is usually constrained to two-dimensional mapping capabilities.[54]

The opportunity to apply PPGIS and CIM in the HIDS project is particularly interesting. They allow the online publication of interactive design scenarios and collection of public comments. In the future, this can also be used as an information and management system (such as in Paris-Saclay's *carte ouverte* discussed above), and as a platform for the planned urban living labs to foster interactive, feedback-based innovation and co-creation processes. In HIDS, geotagging fieldwork data and images is already being employed for mapping natural and historical heritage, and for collecting community and stakeholder input.

Preliminary Studies

Preliminary studies were carried out with PPGIS and CIM tools to generate and evaluate models, simulations and interfaces that can be used for participatory modelling and employed in a future participatory process. Three examples are presented below. The aspects that were subject to evaluation in these tests were social negotiation, urban vitality metrics and landmark placement for legibility in the HIDS project.

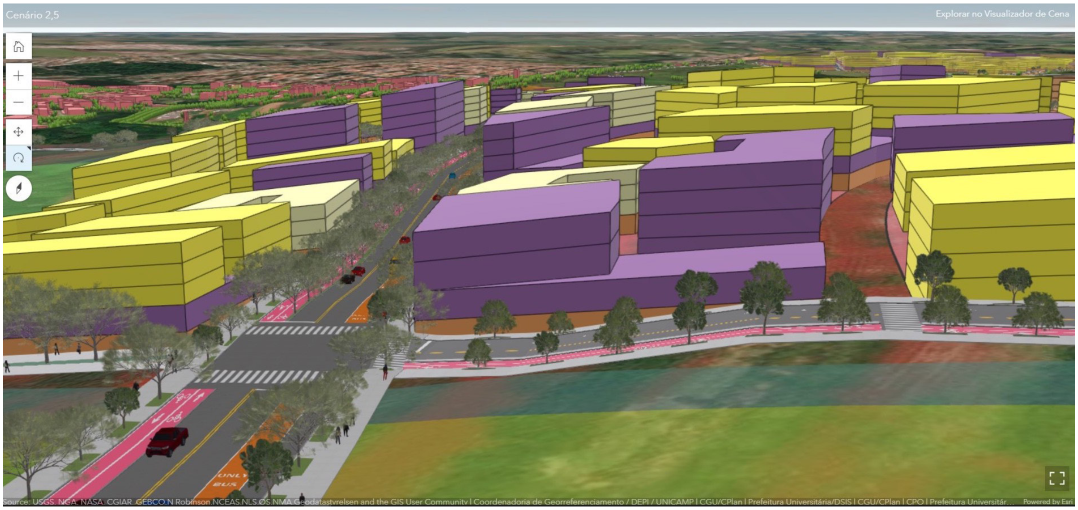
The first study was conducted to test the connection of PPGIS with a CIM tool to allow users to interact with design scenarios, visualize the effect of different input parameters on outputs, and to leave georeferenced comments. Esri ArcGIS Urban and Esri CityEngine were initially tested for modelling HIDS scenarios.[55] A web application to visualize scenarios with varying floor-to-area ratios (FAR) was published online, as shown in Figure 3.[56] Esri CityEngine was used to procedurally model the streets based on walkability rules developed by Sousa, as shown in Figure 4.[57]

53 Frith and Richter, "Building Participatory Counternarratives: Pedagogical Interventions through Digital Placemaking."
54 Gil, "City Information Modelling: Framework."
55 Juan Pietro Cucolo Marçula, "Ferramentas computacionais aplicadas ao planejamento urbano: comparativo e estudo de caso" (UNICAMP, 2021), https://repositorio.unicamp.br/Acervo/Detalhe/1254861; Bárbara de Holanda Maia Teixeira, "Aplicação da modelagem da informação da cidade para planejamento urbano via integração dos softwares CityEngine e Urban" (UNICAMP, 2021), https://repositorio.unicamp.br/Acervo/Detalhe/1258451
56 Marçula, "Modelos 3D do exercício de projeto HIDS," Web Application, 2021, https://hids90e.web.app/home
57 Marcela N. P. O. Sousa, "Retrofitting Urban Streets: Parametric Modeling of Possible Scenarios for Mobility" (Universidade Estadual de Campinas, 2021), https://hdl.handle.net/20.500.12733/6262

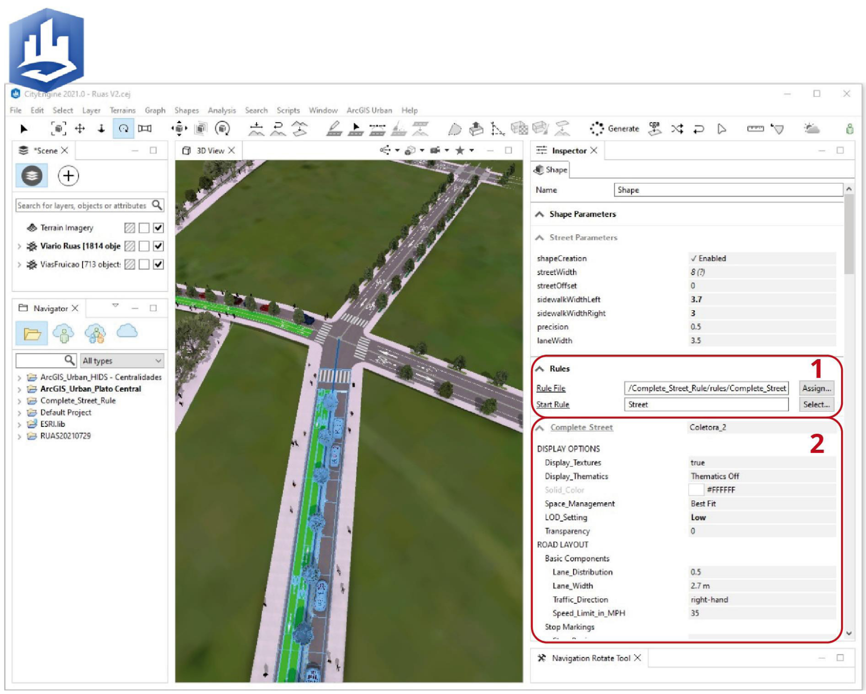
[opposite page]

Fig. 3 HIDS Scenario visualization tool using the Esri ArcGIS Urban Platform, September 2021, (Juan Pietro Cucolo Marçula).

Fig. 4 Inserting a pre-defined rule (1) for complete streets and editing parameters locally (2) in Esri CityEngine software, September 2021, (Bárbara de Holanda Maia Teixeira).



Cenário 2,5
Explorar no Visualizador de Cena



File Edit Select Layer Terrains Graph Shapes Analysis Search Scripts Window ArcGIS Urban Help
Generate
*Scene
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Complete_Street_Rule
Default Project
ESRI.lib
RUAS20210729
3D View
Inspector
Shape
Name
Shape
Shape Parameters
Street Parameters
shapeCreation
✓ Enabled
streetWidth
streetOffset
0
sidewalkWidthLeft
3.7
sidewalkWidthRight
3
precision
0.5
laneWidth
3.5
Rules
1
Rule File
Start Rule
Street
Assign...
Select...
Complete Street
Coletora_2
2
DISPLAY OPTIONS
Display_Textures
true
Display_Thematics
Thematics Off
Solid_Color
#FFFFFF
Space_Management
Best Fit
LOD_Setting
Low
Transparency
0
ROAD LAYOUT
Basic Components
Lane_Distribution
0.5
Lane_Width
2.7 m
Traffic_Direction
right-hand
Speed_Limit_in_MPH
35
Stop Markings
Navigation Rotate Tool

The application allows users to explore the scenarios, from which several quantitative details can be extracted, as seen in Figure 5. It can also be used to collect citizens' opinions on proposed scenarios and to create interactive maps enriched with georeferenced images sent from contributors (see Figure 6). This can be used, for example, to create a map with wild

Fig. 5 HIDS scenario exploration app using the Esri ArcGIS Urban Platform, September 2021, (Juan Pietro Cucolo Marçula).

Fig. 6 Example of a user commenting on a plan in the Esri ArcGIS Urban platform, September 2021, (Juan Pietro Cucolo Marçula).

animals seen in the area by locals, or interesting vegetation. Interactive, web-based applications such as the one presented allow stakeholders and, potentially, communities to gain a higher level of understanding of the scenarios and individual proposals, which can, in turn, provide designers and planners with more qualified input and feedback. Further modelling and scenario building is planned for the coming months, as a decision-support and public participation tool. Further analyses of usability and interface user-friendliness still need to be carried out.

The second preliminary study was the development of an indicator to quantitatively evaluate urban vitality to aid decision-making and policy development aimed at future implementation in a PPGIS system.

Jácome studied different methods for evaluating urban vitality and proposed the adaptation of Koe's system to be applied in HIDS.[58] She conducted a validation study in a Brazilian downtown area acknowledged as very lively. The parameters used by Koe are population density, use intensity, mixed use, functional variety, and public-private ratio.[59] Despite the resulting level of vitality obtained by Gouveia's evaluation in her application study being relatively high, the public-private ratio needs to be adapted to the Brazilian reality. Nonetheless, with the use of Koe's indicators, multiple scenarios can be quantitatively compared. All these parameters can be easily represented and quantified in a city information model and dynamically changed in simulations, contributing to better design results.

Finally, Montefusco conducted a study based on Lynch's legibility theory to develop a parametric empirical model, applying Space Syntax to evaluate scenarios.[60] The procedure was validated by developing a computational model for a consolidated area and comparing the results with a mental map, developed using Lynch's traditional method. This model can be calibrated for different locations based on data crowdsourced using a PPGIS implementation like the one developed by Marçula.[61]

Originally Lynch's theory is applied to consolidated urban areas and uses surveys to map an area's legibility based on five elements: edges, districts, paths, nodes and landmarks.[62] In order to enable the theory's application in urban planning and design, Montefusco developed a procedure based on Space Syntax to evaluate how the location of landmarks and nodes contributes to a scenario's legibility. His procedure was tested using HIDS as an application study.

In the case of HIDS, Montefusco considered that edges, districts and paths were defined a priori by the area's location and municipal legislation and could be sourced from the city's GIS data directly.[63] To evaluate the effects of nodes and landmarks placement on legibility, the author used a scenario developed for a part of HIDS.

The procedure uses angular segment choice analyses to measure the centrality of different streets and isovist fields and cumulative isovists

58 Rita de Cássia Gouveia Jácome, "Vitalidade urbana: diretrizes para induzir padrões de vida urbana no Hub Internacional para o Desenvolvimento Sustentável (HIDS)" (Universidade Estadual de Campinas, 2021), https://hdl.handle.net/20.500.12733/5721; D.M. de Koe, "Urban Vitality through a Mix of Land-Uses and Functions: An Addition to Citymaker" (Wageningen University, 2013).
59 Koe, "Urban Vitality."
60 Marcelo Meloni Montefusco, "A Imagem da (nova) cidade: elementos da imagem da cidade como norteadores de novos projetos urbanos" (Universidade Estadual de Campinas, 2021); Kevin Lynch, *The Image of the City* (Cambridge, MA: MIT Press, 1960).
61 Marçula, "Modelos 3D do HIDS."
62 Lynch, *The Image of the City*.
63 Montefusco, "Imagem da (nova) cidade."

64 Lynch, *The Image of the City*.
65 Tasos Varoudis, "DepthmapX Multi-Platform Spatial Network Analysis Software" (Open Source, 2012); "OpenStreetMap," www.openstreetmap.org
66 Ioulia Kolovou et al., "Road Centre Line Simplification Principles for Angular Segment Analysis," in *Proceedings of the 11th Space Syntax Symposium* (Lisbon: Instituto Superior Técnico, 2017), 163.1–163.16.

with topographic models. This computational procedure was validated in the existing campus area. It was then applied to compare the legibility in two different scenarios developed using a preliminary mass study for part of the HIDS area, called Central Plateau.

According to Lynch's theory, nodes and landmarks are visible from or located on or near the most important paths in a city.[64] To determine the location of these main paths, angular segment choice analyses were conducted in depthmapx using a road centre line map obtained from publicly available GIS files.[65] Before the analyses, the map was simplified and segmented in the QGIS software to reduce angular changes and approximate the results of an axial map, following the procedure described by Kolovou et al.[66] The results of these analyses, shown in Figure 7, are used to predict the most important paths in a scenario, i.e., with the highest potential for vehicle movement — global radius — and pedestrian movement — 400 m radius. This procedure was based on the computational street

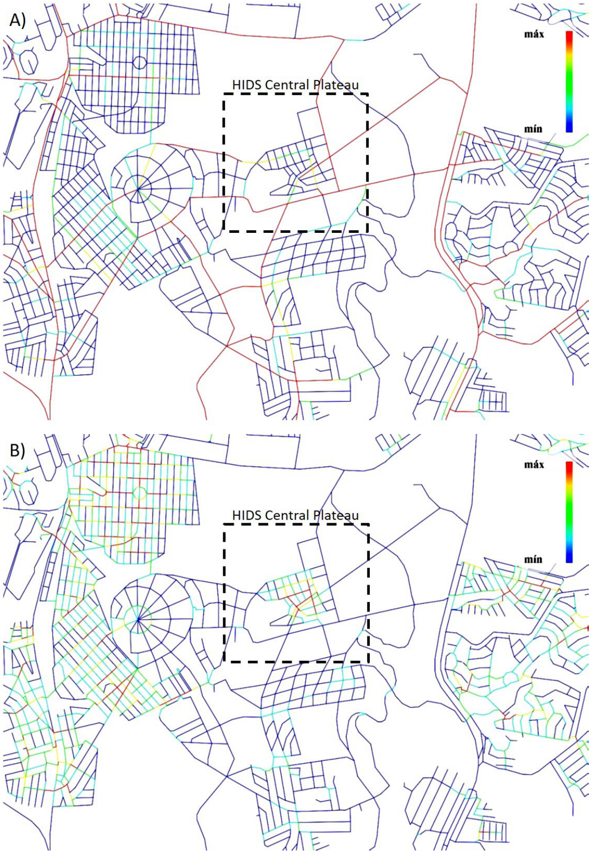


Fig. 7 Angular segment choice analyses for a preliminary scenario for HIDS.
A) Global radius;
B) 400 m radius,
September 2021, (Marcelo Meloni Montefusco).

Fig. 8 Changes made from scenario 1 – original – to scenario 2 – moving or suppressing masses – to evaluate the effect on legibility, September 2021, (Marcelo Meloni Montefusco).

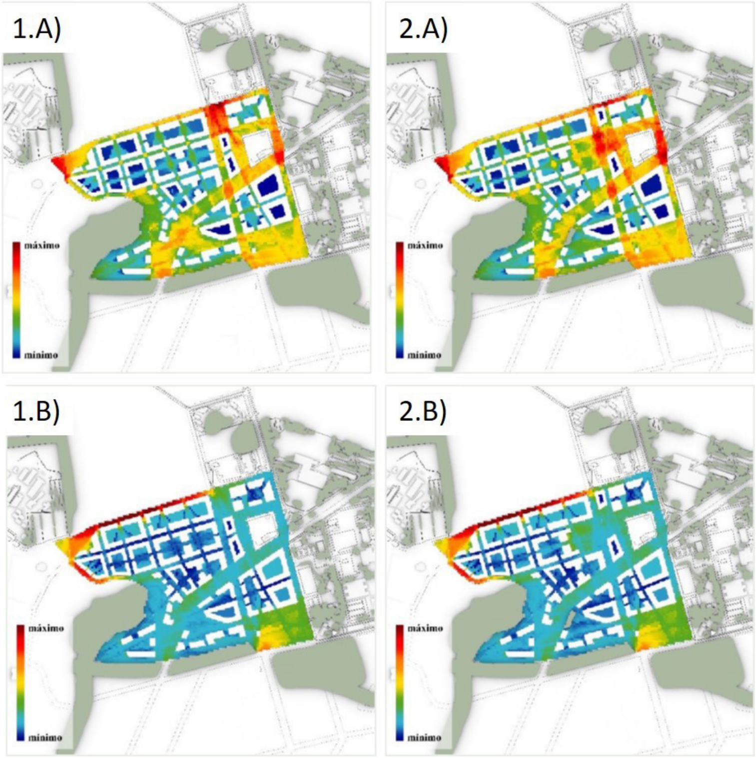
hierarchization method proposed by Sousa, Duarte, and Celani and provides information that, when applying Lynch's traditional method, would have been determined using interviews.[67]

To determine the potential of landmarks and nodes in the scenarios to fulfil these roles, isovist and isovist field analyses were conducted using a parametric model developed in Rhino3D using visual programming in Grasshopper with the DeCodingSpaces Toolbox.[68] The building, vegetation and topography data were also sourced from publicly available GIS files and used to automatically generate a three-dimensional model using attribute data.[69]

Two scenarios were analysed in order to understand the relation between legibility and the geometry of buildings and open areas such as public squares. As shown in Figure 8, small changes were made to the geometry of public squares and building locations from the first scenario to the second.[70]

In this study, Montefusco considered that higher isovist perimeter and occlusivity values define concave spaces.[71] Higher values of circularity and isovist area divided by isovist perimeter are seen in convex spaces with open areas and fewer obstacles. Both types are correlated with the formation of nodes when they coincide with paths with a higher angular segment choice. The highest occlusivity values are correlated with the definition of landmarks, as this is a measure of the place's visibility in the territory. The isovist analyses at eye level for a 400 m radius for both scenarios are shown in Figures 9 to 11. Higher isovist perimeter and occlusivity values are correlated with node formation.

67 Sousa, José Duarte, and Gabriela Celani, "Urban Street Retrofitting – An Application Study on Bottom-Up Design," in *Architecture in the Age of the 4th Industrial Revolution – Proceedings of the 37th ECAADe and 23rd SIGraDi Conference – Volume 3,* ed. J.P. Sousa, J.P. Xavier, and G Castro Henriques (Porto: University of Porto, 2019), 287–96, https://doi.org/10.5151/proceedings-ecaadesigradi2019_233; Lynch, *The Image of the City.*
68 "DeCodingSpaces Toolbox," www.toolbox.decodingspaces.net
69 Montefusco, "Imagem da (nova) cidade."
70 Ibid.
71 Ibid.



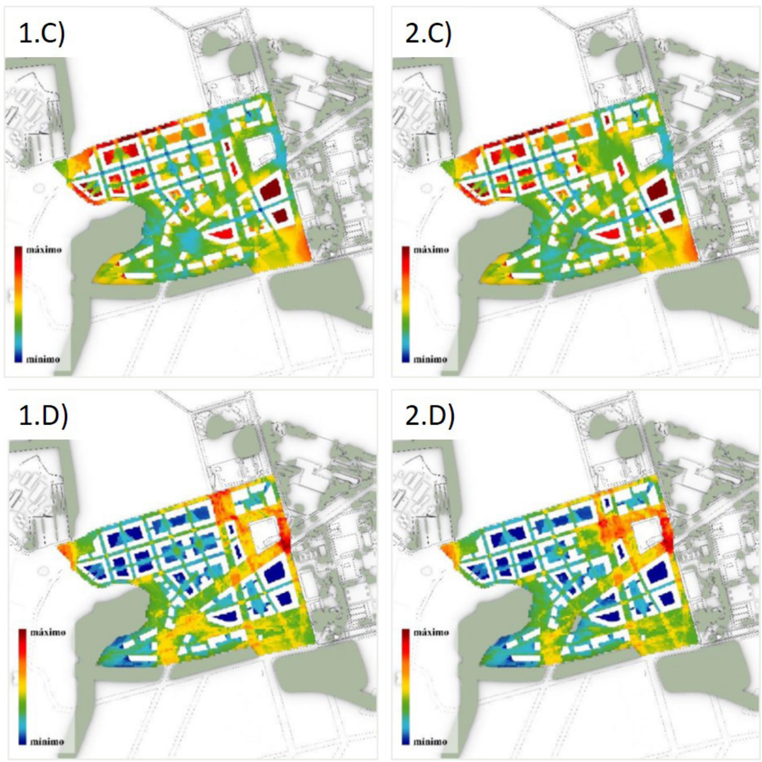
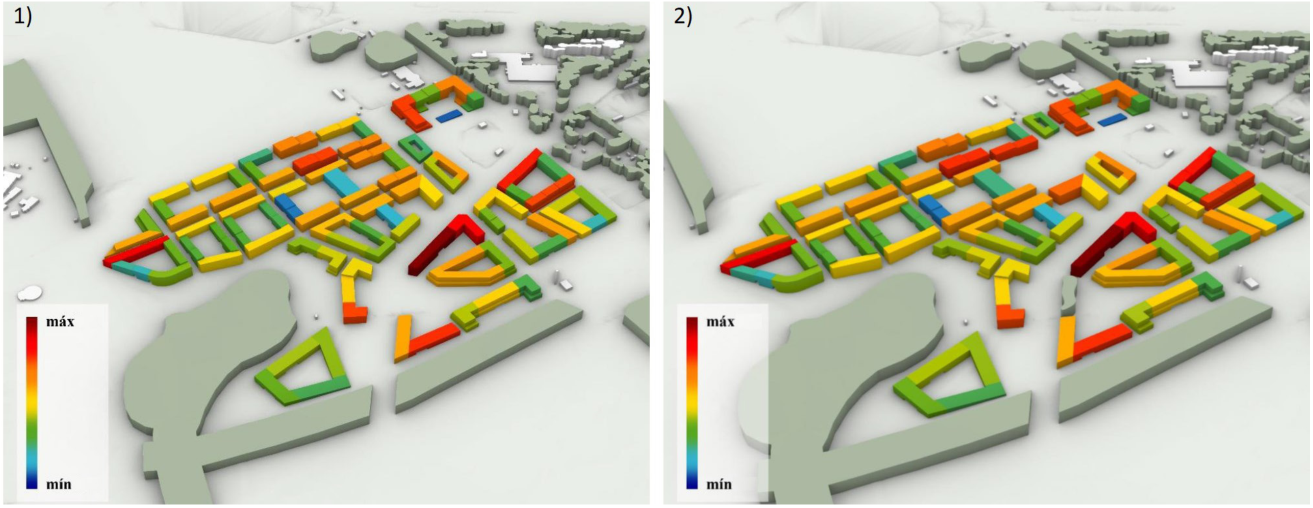


Fig. 9 Isovist analyses at eye level:
1.A) Isovist perimeter for scenario 1;
2.A) Isovist perimeter for scenario 2;
1.B) Ratio of isovist perimeter to isovist area for scenario 1;
2.B) Ratio of isovist perimeter to isovist area for scenario 2, September 2021, (Marcelo Meloni Montefusco).

Fig. 10 Isovist analyses at eye level:
1.C) Isovist circularity for scenario 1;
2.C) Isovist circularity for scenario 2;
1.D) Isovist occlusivity for scenario 1;
2.D) Isovist occlusivity for scenario 2, September 2021, (Marcelo Meloni Montefusco).

Fig. 11 [opposite page]
Cumulative isovists of HIDS Central Plateau
1) Scenario 1;
2) Scenario 2, September 2021, (Marcelo Meloni Montefusco).



72 Ibid.

From one scenario to the next, it can be seen how these small changes to building masses can change the location of zones with higher isovist perimeter, area and occlusivity values, making them coincide with important routes in the plan. This concurrence of different measures in the same place favours the formation of nodes and landmarks, contributing to an area's overall legibility.[72]

This type of empirical model implemented in CIM, shared and collaboratively evaluated using PPGIS, can improve data collection and support decision-making, while providing a more transparent design process to reduce conflict between stakeholders in a participatory design process.

Discussion and Conclusion

In this paper we presented a review of the knowledge economy and the different generations of science parks. We proposed a fourth generation that combines the concepts of knowledge-based urban developments and urban fringes, in line with the quintuple helix innovation model. Next, we illustrated this generation with the case of Paris-Saclay. Finally, we presented the case of HIDS, which is a retrofit of a second-generation park into a fourth-generation territory. We discussed how PPGIS and CIM can be used for different purposes in participatory modelling to help in the public engagement and placemaking of this type of development.

The preliminary studies presented in this paper are a contribution to participatory processes by aiding visualization and communication and by collecting knowledge and data that can be used as input for empirical modelling and scenario testing. We showed how these methods can be employed during the design phase to simulate and evaluate the often elusive urban qualities of vitality and legibility.

The main advantage of using PPGIS for participatory modelling is its potential to facilitate and consequently increase public engagement through web-based input collection and communication applications, increasing data volume, reliability and significance. When extended with CIM, parametric and simulation-based modelling, these tools can be used to improve citizens' comprehension of design, planning and legislative proposals. This increases their ability to make purposeful and knowledgeable contributions to the process, assisting in the reduction and resolution of conflicts stemming from poor communication between stakeholders.

These approaches are in line with the bottom-up, feedback-based innovation which KBUDs are based on. Nevertheless, the collaboration between academia and the public realm can be tricky since each of them operate on different timescales. In the case of HIDS, the application of the tools for simulation-based participatory modelling presented herein is largely dependent on a political process that cannot be accelerated. Still, we expect that these preliminary studies can contribute to other similar projects.

As the post-pandemic relationship between work and place dissolves and more of our activities migrate to the digital realm, so must the tools for urban planning and participatory engagement. Science parks and districts will have to engage firms, institutions and communities by offering more than just office space. They will have to contribute to a sense of place and belonging in order to be relevant in the digital culture. The use of PPGIS, CIM and digital placemaking are aligned with the concept of KBUD as they enable planners and designers to deal with complex phenomena, receiving feedback through simulations, and by engaging stakeholders and communities.

Beyond the issues discussed in this paper, urban fringe KBUDs pose many other challenges for traditional urban planning due to their complexity in terms of land structure, green and grey infrastructure, sustainable land use, science and research equipment, housing, etc. These are important issues that must be addressed in any KBUD, both in developed and developing countries.

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Mathilde Marengo
Advanced Architecture Group, Institute for Advanced Architecture of Catalonia, Barcelona, Spain

Iacopo Neri
Advanced Architecture Group, Institute for Advanced Architecture of Catalonia, Barcelona, Spain

Eduardo Rico-Carranza
Architectural Association, London, UK;
Faculty at the Institute for Advanced Architecture of Catalonia's Master in City & Technology, Barcelona, Spain

Simulating Ecological Connectivity and River Behaviour for Dynamic Territorial Mapping

An Analytical Methodology to Support Data-driven Workflows for the Design of Living Cities

Keywords
— ecological modelling; computational design; territorial mapping; design with nature; living cities

DOI
— 10.14195/1647-8681_14_6

Centres for human life, cities represent the main threat to fine ecological balances, which are in turn responsible at multiple levels for the health of citizens. Metropolitan areas are therefore key in addressing such issues to maintain the well-being of all living things. Within today's digital culture, designers have the opportunity to face these unprecedented challenges by approaching landscape under a dynamic, collective, multidisciplinary and multiscalar perspective, enabled through digital tools and data driven processes. These enablers have the potential to empower designers to engage with nature as an active partner, gaining a new understanding with which to represent these landscapes. The article discusses an experimental methodology for the analysis of urbanised ecological territories that detect and amplify potential and beneficial ecological connections or embedded behaviours, providing an opportunity to use this as the basis to design cities consciously for, and within, climate change adaptation.

Urbanisation today represents the main threat to fine ecological balances. Home to the majority of citizens across the globe, cities are considered to cover 3% of the world's surface, yet 70% is transformed by human processes into a state of rapid alteration.[1] This creates ever growing risks for the ecology, and is also responsible at multiple levels for the health of the citizens inhabiting these spaces. In this sense, urbanised areas, and consequently their design and planning, are key in addressing such issues, in order to maintain the well-being of all living systems.

Despite the fact that the relevance of restoring green and blue infrastructures, for the mitigation of human impacts over natural systems, is certain and institutionalised – the Paris Agreement, SDG 14 and 15, the European Green Deal[2] – the pathways to reach such an objective are not always clear. To this end, rewilding and renaturing processes, as conservation strategies, have recently experienced a wave of attention from scholars and politicians thanks to their potential for restoring anthropocentric landscapes to a higher level of ecological prosperity. Yet, they have proven to be difficult to assess and often – due to deficiency in governing the implicit complexity – resulted in unexpected scenarios where the initial issue, if not unaltered, was simply transferred or further amplified.[3]

These approaches are often undertaken in order to counteract the impacts of anthropogenic pressures on the ecology, rather than empowering ecology to actively adapt within today's highly urbanised world, becoming an active partner within the definition of this transition. This is highlighted by the fact that the great majority of today's legal systems only protect the rights of humans, often considering nature as one of the resources to be exploited "for the exclusive benefit of our own species".[4] Although this legal condition has begun to shift with the emergence of several national and international conventions, ordinances and even the revision of some constitutions, the modus operandi applied until this shift has created a condition whereby land and ecology, through property laws, have been fragmented; a condition that is in profound "contradiction to ecological principles of wholeness and interconnection."[5] Within the realm of urban design and planning, this condition raises the essential question of how nature and ecology can have an operative voice there as well.

To this end, concepts such as renaturing and rewilding – both intended to not only restore nature, but allow it to thrive independently – offer an unprecedented challenge for designers: to approach landscape under a dynamic, collective, multidisciplinary and multiscalar perspective. Whether by the identification of keystone animal species, as major landscape constructors, or by the simulation of major territorial dynamics, happening in distinct time scales, these frameworks have the potential to empower designers with a new set of tools to understand and represent territorial urban ecologies. In doing so, they reconsider the polarisation

1 Alice Siragusa, Michele Melchiorri, Martino Pesaresi and Thomas Kemper, eds., *JRC. Atlas of the Human Planet 2016: Mapping Human Presence on Earth with the Global Human Settlement Layer* (Luxembourg: Publications Office of the European Union, 2016), available at https://data.europa.eu/doi/10.2788/889483; Alex de Sherbinin, A *CIESIN Thematic Guide to Land-Use and Land-Cover Change (LUCC)* (Palisades, NY: Center for International Earth Science Information Network (CIESIN), Columbia University, 2002). https://sedac.ciesin.columbia.edu/binaries/web/sedac/thematic-guides/ciesin_lucc_tg.pdf

2 https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement; https://www.un.org/sustainabledevelopment/oceans/; https://www.un.org/sustainabledevelopment/biodiversity/; https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

3 International Union for Conservation of Nature and Natural Resources, and Species Survival Commission, *Guidelines for Reintroductions and Other Conservation Translocations* (Gland: IUCN Species Survival Commission, 2013). https://portals.iucn.org/library/efiles/documents/2013-009.pdf

4 John Thackara, *How to Thrive in the Next Economy: Designing Tomorrow's World Today* (London: Thames and Hudson, 2015), 151-156.

5 https://www.garn.org/universal-declaration/; https://www.smgov.net/departments/council/agendas/2013/20130409/s20130409_07A1.htm; https://pdba.georgetown.edu/Constitutions/Ecuador/ecuador.html

between environmental forces and anthropocentric ones and provide an opportunity to use this process as the basis for embedding nature as an active partner, and to consciously design cities for, and within, climate change adaptation. In order to facilitate the operability of this paradigm shift in terms of urban planning and design, there is a clear interest in embedding data-driven approaches – computational modelling, data analytics, simulation, and more – taking advantage of the large availability of datasets, often accessible as open data. In fact, with the emergence of the *Information Age* and its evolution into the *Experience Age*, these shifts bring new principles and technologies with which to rethink not only the functioning and structure of the spaces we inhabit, but also of the way in which we design them.

The body of work that follows introduces and discusses an experimental methodology for the analysis of urbanised ecological territories enabled through the contemporary digital culture, producing a shift within the realm of these disciplines in order to actively engage with ecology, as a partner, within their development. Specifically, this methodology detects and amplifies potential and beneficial ecological connections within urban and non-urban areas, in order to potentiate the ecological performance of the system as a whole, towards the development of strategies for life-centred and resilient cities. It does so by embracing the complexity of cities, their surrounding territories and their ecological systems at multiple scales of analysis, and by identifying site-specific major drivers of change to support this process. In this regard, the proposed data-driven methodology uses computational logics exploited in environmental studies to foresee ecological patterns for analysis and validation purposes, which can then feed design pipelines. To this end, the paper collects the work produced within the Institute for Advanced Architecture of Catalonia's (IAAC) research and educational environment, including two years of experimentation alongside students of IAAC's Master in City & Technology, showcasing the results, developed in the cities of Barcelona, London and Luxembourg. From the simulation of fauna movement, with circuit theory algorithms, to the territorial one of river flooding patterns, through cellular automata, the paper offers a multi contextual benchmark for the comparison of sustainability-related assessment methodologies and some design explorations developed within an educational environment.[6] This consequently provides an overview on viable analytical and territorial mapping approaches – enabled by ecological data and simulations – that inform designers from two main collaborative perspectives: developing territorial solutions in collaboration with river systems, and with fauna dynamics, both engaged as active partners to feed the design process with newly found ecological potential. This becomes the basis with which to effectively and dynamically design for the ecological transition of urban areas.

6 Viral Shah and Brad McRae, "Circuitscape: A Tool for Landscape Ecology," in Gael Varoquaux, Travis Vaught, Jarrod Millman, eds., *Proceedings of the 7th Python in Science conference* (SciPy 2008), 62-65, https://conference.scipy.org/proceedings/SciPy2008/SciPy2008_proceedings.pdf; Marco J. Van De Wiel, Tom J. Coulthard, Mark G. Macklin and John Lewin, "Embedding Reach-Scale Fluvial Dynamics within the CAESAR Cellular Automaton Landscape Evolution Model," *Geomorphology,* vol. 90, no. 3 (October 2007): 283–301.

7 R. T. Paine, “A Note on Trophic Complexity and Community Stability,” *The American Naturalist 103,* no. 929 (1969): 91–93.

8 Sanne de Visser, Elisa Thébault and Peter C. De Ruiter, “Ecosystem Engineers, Keystone Species,” in Rik Leemans, ed. *Ecological Systems: Selected Entries from the Encyclopedia of Sustainability Science and Technology* (New York: Springer, 2013), 59–68.

Ecological Connectivity to Support Ecosystem Engineers as Active Partners in Design

Actively engaging with the metropolitan area of a city challenges designers with a set of constraints and possibilities that increasingly step away from the realm of the designed or planned. In this manner, dealing with landscape as an active force for design implies a hierarchical identification of actors, which goes beyond the pure human-centric perspective of nature/artifice, rethinking design as a series of actions in continuous disturbance with the surrounding environment, and therefore, as a dynamic and open system. In this regard, since the 70s, ecologists have been referring to the concept of keystone species as those animal or plant species whose activities exert a disproportionate influence on the patterns that define an entire ecosystem.[7] More specifically, ecosystem engineers, defined as organisms that alter the availability of resources in a territory while physically shaping it, represent a unique opportunity for collaboration with designers to achieve long-lasting design intentions, which are not only resilient – as produced by living organisms – but can also autonomously thrive, and adapt – expand or shrink – if necessary.[8]

Simulating the likelihood for these natural engineers to thrive in heterogeneous landscapes, such as in the metropolitan areas of many cities around the world, as well as the territorial consequences of their living, is crucial for their inclusion in the design process. The following section introduces three case studies where the simulation of insect pollinators, beavers, and bats is used to drive a design process to restore degraded landscapes in the metropolitan regions of Barcelona, Luxembourg and London. The adopted methodology exploits ecological connectivity, as expression of the implicit and planned tensions between these fragmented landscapes, in order to study, filter, and later validate design decisions that directly impact the aforementioned ecosystem engineers.

The Case Studies of FlowerPowder, [Echo]nnect, and Rewilding Luxembourg

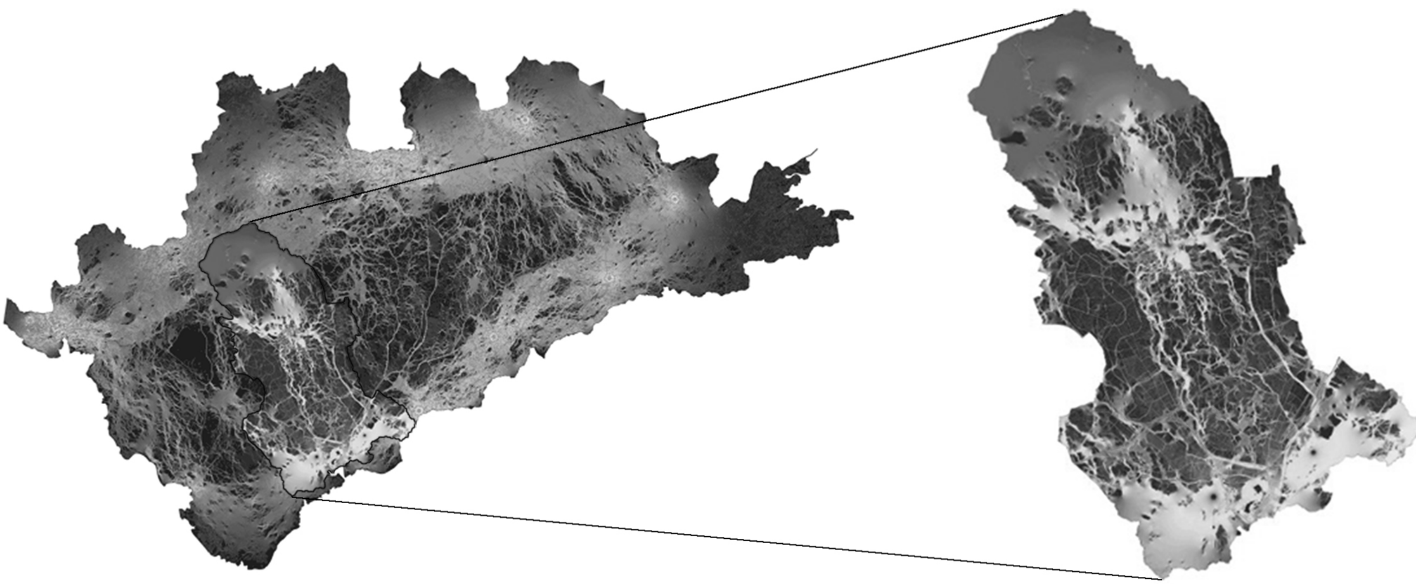
Metropolitan areas are by definition fragmented landscapes resulting from the uncoordinated initiatives of different stakeholders, at different scales. In these conflicting contexts, changes in land use often echo into uncontrolled consequences that deeply impact surrounding areas and, therefore, need to be tackled at a wider dimension compared to the one where the physical changes apparently take place.

Engaging with renaturing and rewilding concepts as strategies to drive such dynamics, the case studies of FlowerPowder, [Echo]nnect and Rewilding Luxembourg offer an operational and context-specific framework to dynamically understand, and later design, within fragmented landscapes, towards achieving restoration goals. While focusing on three different global issues (post-agrogenic lands, wetlands loss, and urban sprawl), and collaborating with three different keystone species (insect pollinators, beavers, and bats), they all exploit ecological connectivity analysis – computed through the open source Circuitscape application – as means to overcome the aforementioned territorial fragmentation and identify ecologically relevant areas and corridors to support through design and citizen engagement.

Compared to traditional practices, the case studies show that basing design on the application of data-driven tools such as Circuitscape allows not only a detailed understanding of complex land-interactions between fragmented landscapes under current conditions to be obtained, but also design decisions to be computationally empowered, as the effect of planned land change can be visualised and assessed within the scope of each design intention.

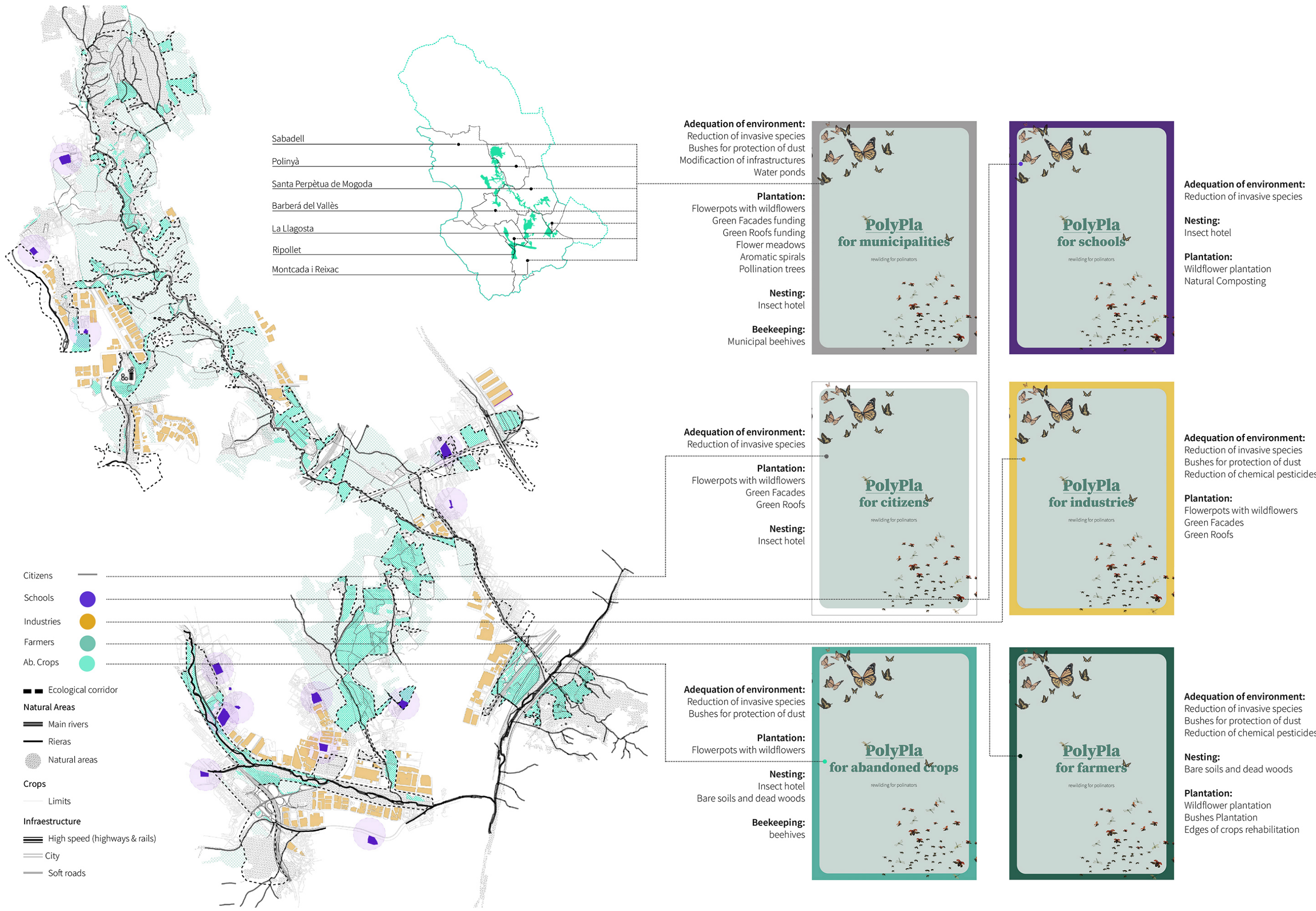
More specifically, considering ecological connectivity in heterogeneous landscapes as performing similarly to electrical current in heterogeneous material, they predict the main flows of ecological exchange according to land-specific degrees of conductance for each of the keystone species selected, before and after their design implementation. By simply altering the conductance with pre- and post-intervention values (low conductance to higher conductance), they actively engage with the territorial dynamics to design, and in this manner, through design they successfully identify and support assets crucial for the accomplishment of the restoration goals within a general set of land-change opportunities. (Figure 1)

Fig. 1 The image illustrates the scaling down process within the El Vallès area to identify crucial areas for ecological connectivity at multiple scales. FlowerPowder. Developed by students Adriana Aguirre Such, Simone Grasso, Matteo Murat, Riccardo Palazzolo Henkes. Master in City & Technology, IAAC, Barcelona, 2021.



FlowerPowder: Revitalising the Abandoned Crops of el Vallès through Contextualised Participation

Inspired by rewilding approaches, the FlowerPowder case study engages with the issue of abandoned agricultural plots fostered for the design of ecological corridors that act as both spatial and analytical tools to coordinate human stakeholders and pollinators – as ecosystem service providers – in a process of revitalisation for these degraded landscapes. Focusing on the region of El Vallès, in the metropolitan area of Barcelona, it exploits ecological connectivity presented in maps to visualise dynamisms along the north-south axis while scaling down from the regional to the



municipal scale. This process allows, the most relevant areas at every scale to be highlighted – those with the highest ecological potential in relation to the corridor as a whole – to initiate the process of revitalisation. In this regard, using connectivity as a metric to select key locations permits effort and cost to be minimised while maximising results, since the echo of the localised interventions is guaranteed to resonate on the broader ecosystem, at the regional scale.

A largely altered territory, the area of El Vallès offers an interesting case study where the coexistence between natural and anthropogenic ecosystems, historically relevant for agriculture but in decline since the beginning of the 20th century, has resulted in a highly diverse and fragmented territory including urban settlements, large cultivations and industrial districts. These fuse together in a heterogeneous valley surrounded by a system of protected highlands – the Prelitoral and Litoral mountain ranges – respectively on the northern and southern limits. For this reason, in support of the connectivity analysis conducted between the protected patches at the limits of the valley, a categorisation of the abandoned crops identified as relevant for the activation process was carried out in order to give specificity to each plot based on its local and surrounding land-use conditions. This resulted in the definition of five categories: inside a natural ecosystem, between two or more natural ecosystems, between a natural and an anthropogenic ecosystem, between two or more anthropogenic ecosystems, inside an anthropogenic ecosystem. The categories add a qualitative perspective to the merely quantitative understanding of each plot's connectivity potential, therefore laying the ground to support the following participatory process with specific human stakeholders and spatial conditions, in support of pollinators.

These considerations are gathered and used to trigger the design of the Polypla participatory process, which comprises a set of guidelines and actions enabling each location, in consideration of its specificity, to reinforce the proposed pollinator corridor. This therefore condenses into meaningful activities based on the insights gained through the correlation of connectivity, land uses, and stakeholder maps at multiple scales of analysis (Figure 2).

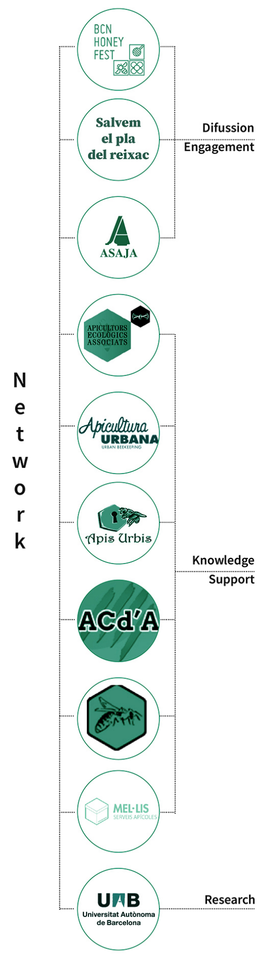


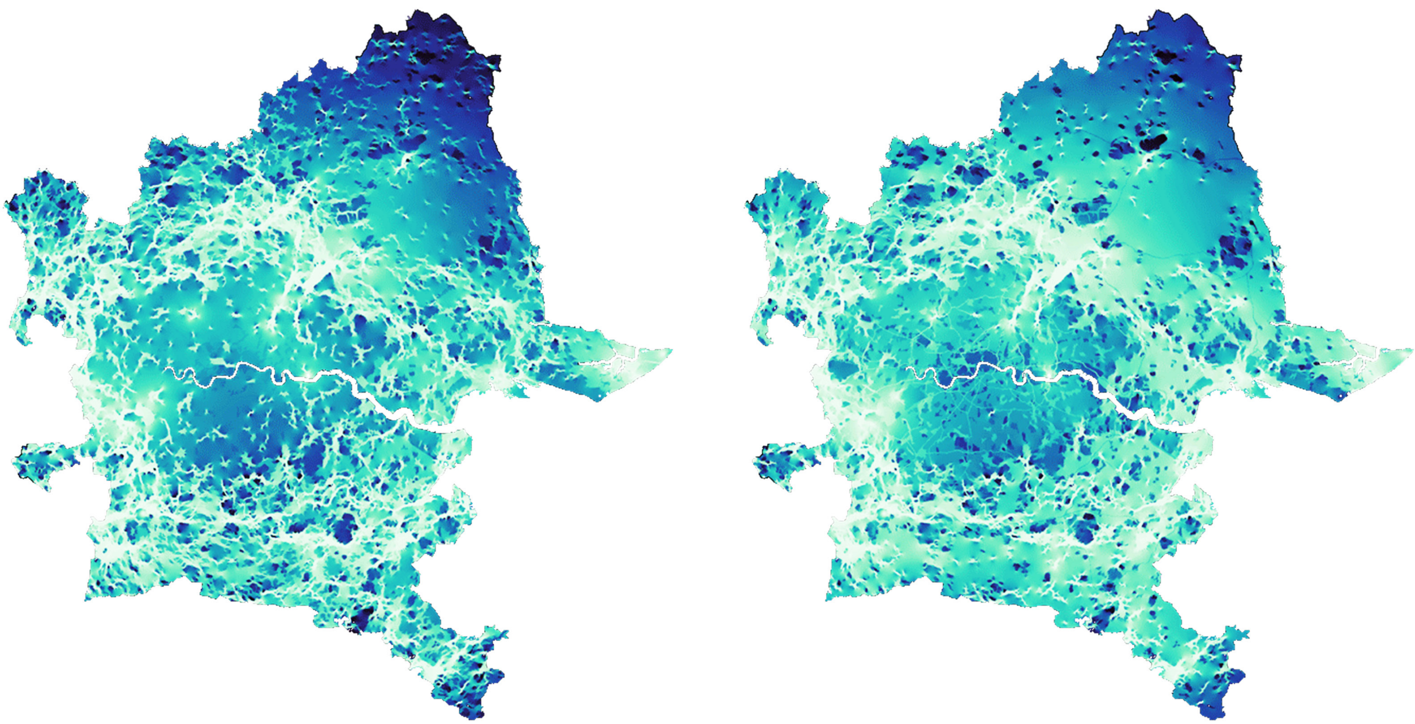
Fig. 2 The Polypla initiatives and the proposed stakeholders. FlowerPowder. Developed by students Adriana Aguirre Such, Simone Grasso, Matteo Murat, Riccardo Palazzolo Henkes. Master in City & Technology, IAAC, Barcelona, 2021.

[Echo]nnect: Establishing Mutually Beneficial Partnerships with Ecosystem Agents

From pollinators in general to bats in their role as ecosystem service providers and moving from Barcelona to focusing on the metropolitan area of London as a test bed, the [Echo]nnect case study introduces a strategy to plan the conversion of highways into ecological corridors. This case foresees a necessary reduction in private vehicular traffic over the coming years, and encourages a possible future where such infrastructure, due to its conformation, could become infrastructure for alternative transport and diversity of species. Challenged by the pioneering objective of the English metropolis to be independent from cars by 2030, the project exploits ecological connectivity analysis to evaluate the potential of the roadways in mending and reconnecting the highly fragmented metropolitan area of London.

In this sense, Epping Forest was identified as a promising gateway between the system of outer patches and the internal parks, highlighting a section of the A406 trunk road as an area of interest, allowing the potential of ecological connectivity to multiply across different scales (Figure 3). A catalogue of interventions is consequently proposed to facilitate the repurposing of the aforementioned infrastructure into a catalyst for bats – considered a celebrity species – to thrive, according to the spatial, economic and societal conditions – connecting lower and higher income communities – of the specific surroundings. The interventions were proposed in three main spatial conditions: urban settlements, infrastructure, and natural areas, to be activated on different scales, and encouraging the bats to further proliferate in the area and become agents to enhance biodiversity and ecological connectivity.

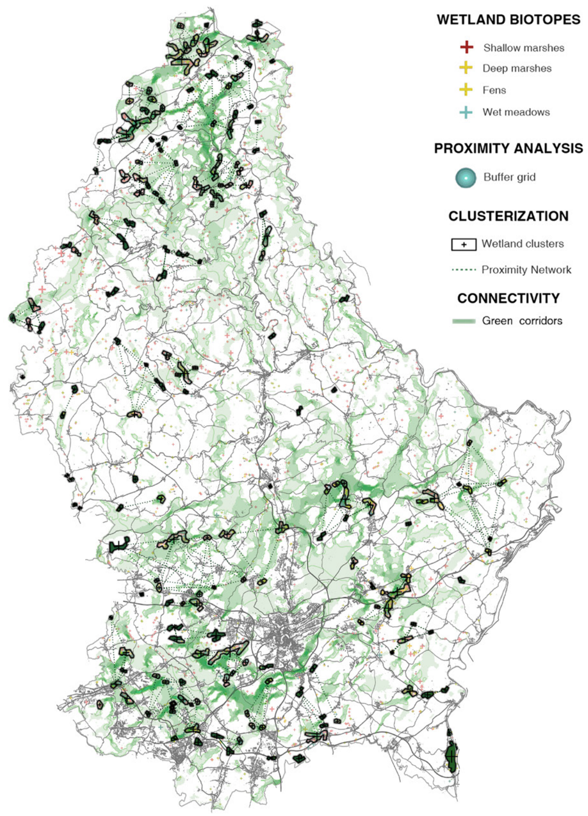
Fig. 3 Connectivity studies for the metropolitan area of London. On the right, the simulation considers the road infrastructure with high connectivity values. [Echo]nnect. Developed by students Dimitrios Lampriadis, Joseph Bou Saleh, Julia McGee, Kriti Nirmal. Master in City & Technology, IAAC, Barcelona, 2022.



Rewilding Luxembourg: Empowering Ecosystem Engineers through Citizens Science

Challenging the binary view of existing rewilding strategies in human and non-human realms, the Rewilding Luxembourg case study proposes an integrated framework between species and for both planning processes and co-management strategies – supported by ecological connectivity studies – to compensate for the nation's critical level of landscape fragmentation. In Luxembourg, ongoing urban sprawl and the consequent infrastructural requirements, alongside the relatively limited dimensions of the country, have generated one of the most fragmented territories of the European Union, constantly threatening its constituent habitats. As wetlands have been registered as having experienced the highest habitat loss, the case study calls upon beavers to play an active role as ecosystem engineers in the restoration of these threatened areas, working collaboratively alongside children, as cross-species collaborators and citizen scientists, in order to trigger a behavioural change which would guarantee the long-lasting achievement of its restoration goals (Figure 4).

Fig. 4 Wetland connectivity map, with darker green areas showing higher attractivity for beavers' activities Rewilding Luxembourg. Developed by students Alvaro Cerezo Carrizo, Arina Novikova, Dongxuan Zhu and Stefania-Maria Kousoula. Master in City & Technology, IAAC, Barcelona, 2021.



For this reason, community engagement and co-management become key elements within the conversion process in parallel with the connectivity analysis, constituting a base understanding of the most favourable locations for beavers to thrive and therefore succeed in the ecological restoration process. To this end, an initial ecological connectivity analysis among the wetlands at the regional scale is further cross-read with the proximity to primary and secondary schools, providing a necessary spatial understanding for the implementation phase, which indicated the city of Bertrange, in the south-western area of Luxembourg, as an ideal test bed. Similarly to the case study of FlowerPowder, the change in scale is further strengthened by higher-resolution connectivity studies, which allowed trial fields along the river Petrusse to be identified as a system of core and buffer areas at the intersections between the human and the wetland infrastructures. This design framework has spatially allocated different degrees of responsibility and freedom of action to beavers, exclusive dwellers of the core restoration zones, and to children, monitoring partners of the buffer zones. This permits the resilient co-management of the restoration process while providing a fruitful case study of multi-species collaboration to assess rewilding strategies. The project also foresees the monitoring and continuous collection of data in order to measure the impact and success of the approach, through a citizen science approach.

Simulating Flooding Patterns to Engage with River Systems

Rivers, and waterbodies more in general, might not be as invisible to the eye of the designer as a community of keystones species that dwell in a specific habitat. Yet their highly dynamic nature, taking place at such drastically different rhythms and scales from ours, constitute a highly complex challenge from both the conceptual imagery and from a tangible perspective for design. Despite this, climate change, alongside the recent catastrophic floods, the decline in species diversity, and more generally river pollution, represent issues that can no longer remain unaddressed, both within urban and rural contexts. This therefore leaves designers with no option but to strategically interact with these territorial water forces.

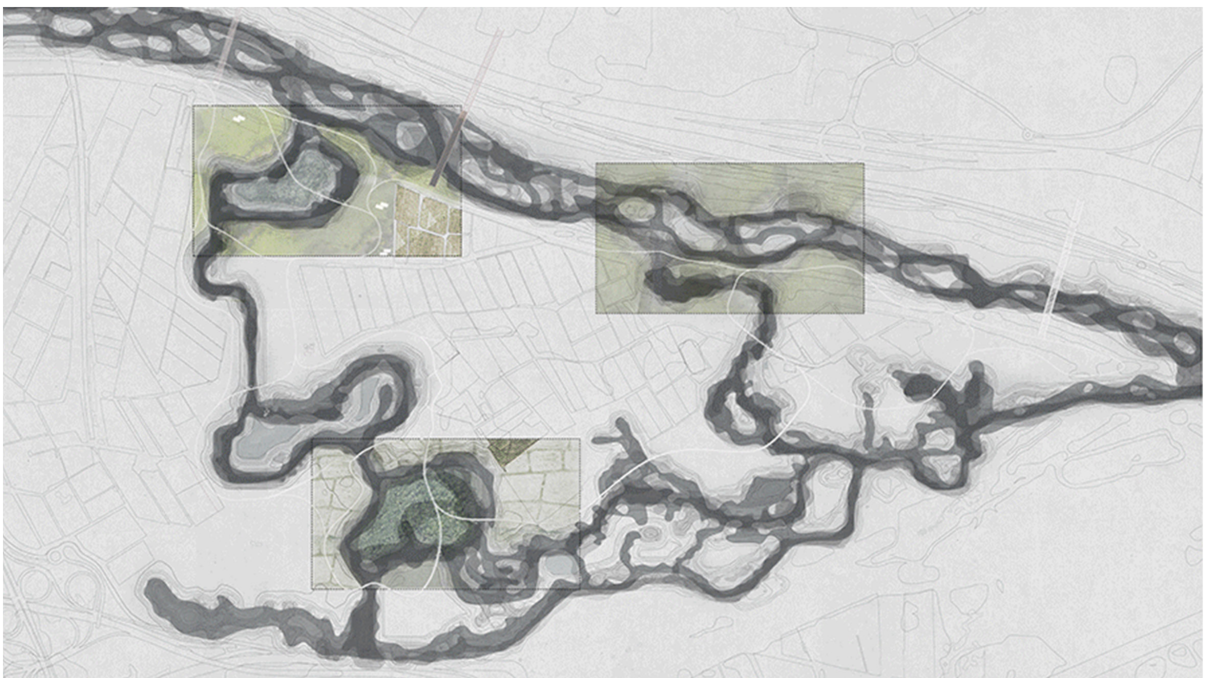
In this fluid context, unforeseen changes, both in the water course as well as in its immediate surroundings, have the potential to alter areas kilometres away from the original site with undesired consequences for both the environment and society. Actively engaging with rivers within the design process means understanding, foreseeing, and finally driving the dynamics resulting from specific interventions in order to emphasise, rather than limit, the design through, and with, floods. To this end, two case studies are presented that computationally delve into river systems and their renaturalisation, in the metropolitan contexts of Barcelona, and Luxembourg, respectively for the Llobregat and Alzette rivers.

The Case Studies of Re(naturing) BCN and Alzette 2.0

Rivers are highly complex systems, and are in principle highly natural systems, yet due to the vast amount of human interventions within their morphology, notably river bed modifications, these rivers lose their capacity to function naturally, causing both flooding and loss of habitat. The case studies of Re(naturing) BCN and Alzette 2.0 – River Re-visioning both engage with river renaturing, meaning different strategies and techniques applied to enhance the natural state and functioning of rivers and catchments, in order to tackle these challenges. The case studies aim to assist this recovery and increase resilience by addressing hydrological, morphological and biological issues within the river catchment.

In order to understand and design with such dynamic complexity, hydrological simulations of both cases were performed using the CAESAR Lisflood morphodynamic model allowing study of the behaviour of the rivers. This also allows the introduction of new meanders and channels based on hydrogeological analysis, as well as rainfall data, in order to extract the preferred conditions for the river through dynamic simulations, in adaptation to flood risk and habitat loss (Figure 5). In order to implement these preferred and dynamic configurations for the river to renaturalise its habitat and functioning, both cases engage in the revaluation of land use

Fig. 5 The image shows the final stage of the river expansion simulated with CAESAR Lisflood and contextualised within a multi-phase design intervention. Re(naturing). Developed by students Aishath Nadh Ha Naseer, Hebah Qatanany, Laura Guimaraes, Mario Jose Gonzalez, Sinay Coskun. Master in City & Technology, IAAC, Barcelona, 2021.



within the river bed, enabling the integration of nature based solutions, to tackle pollution issues, as well as reduce soil erosion and improve biodiversity, allowing the ecosystem to thrive holistically.

Re(naturing) BCN: Integrating Hydrologic and Urban Expansions

With an extensive history of human interventions, the Llobregat river is the second longest stream of Catalonia, in Spain, and represents a crucial resource for the region. Springing from the mountains of Sierra del Cadì, the watercourse flows for 170 km before reaching the metropolitan area of Barcelona where it dives into the Mediterranean sea. Along its riverbanks, several industrial and other economic activities take place, ranging from textile industries and factory towns to agricultural fields, as well as hosting quarries that have been active since Roman times. Such a complex and resource intensive system resulted in the environmental degradation of the river, culminating in the delta area, where the challenges of increasing flooding and water pollution currently question the plans of urban expansion of the city of Barcelona.

Here is where the focus of the project is placed. Blending morphological dynamism with anthropogenic interests, the Llobregat Delta embodies a high level of complexity that requires an in-depth analysis from both a spatial and temporal perspective. For this reason, the methodology introduces river flooding simulations on which to base the future development of the area, which structures the proposed intervention into five phases, adaptively integrating the hydrologic forces into the planned urban tissue. Computing the river expansions through the CAESAR Lisflood toolkit allowed not only such territorial processes to be visualised, but also the results to be cross-read with additional datasets describing other conditions of the landscape, such as in the case of its land use (Figure 6). Relevant to the economic prosperity of the delta area, an impact assessment ranking the local farmlands from mildly influenced to severely affected was calculated as per the extension of overlap between the agricultural plots and the simulated riverbank. By identifying the trade-offs for this renaturing process to happen at the expense of the local businesses, the methodology aims at using data and simulations to provide a base understanding for further design accurate compensation plans for the most afflicted communities. There is also the possibility of triggering collaborative and participatory processes involving both the food industry and the farmers in order to accentuate these.

Alzette 2.0: Informing Participatory Process with Long-Term River Visions

Similarly to the case study of Re(naturing) BCN, the methodology proposed in Alzette 2.0 aims at mitigating the consequences of river renaturation processes, from hydrological, morphological, biological and societal perspectives. Home to the largest catchment area of the nation, the Alzette

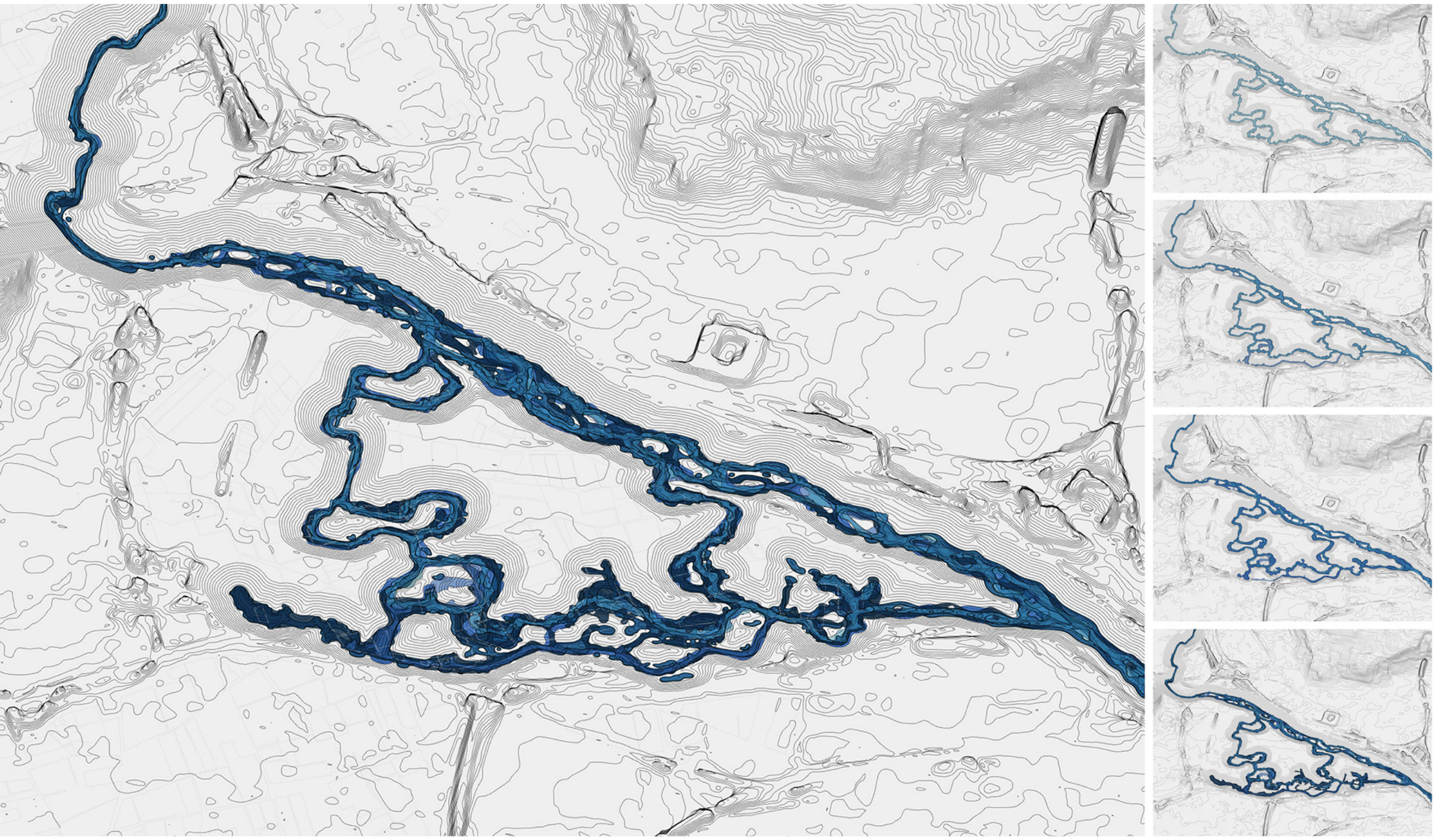


Fig. 6 Phases of the river flooding simulation in CAESAR Lisflood cross-read with the existing agricultural fields. Re(naturing). Developed by students Aishath Nadh Ha Naseer, Hebah Qatanany, Laura Guimaraes, Mario Jose Gonzalez, Sinay Coskun. Master in City & Technology, IAAC, Barcelona, 2021.

river receives a dangerous level of pollutants, specifically in the proximity of urban settlements, majorly visible in the surroundings of Luxembourg. Following an initial territorial risk assessment concerning population density, water pollution levels and ecological status, as well as the location of mines and disposal facilities to mention a few, two main areas are identified, respectively, in the upstream valleys of the Esch-sur Alzette canton and at the doors of the city of Luxembourg. Tackling water pollution from the very beginning of the stream and alleviating the risk of flooding before entering the urban fabric, these strategic locations were further analysed to study the river's behaviour according to several rainfall data and design configurations.

In this sense, the adopted methodology engaged with the design of the meandering intervention through a data-design feedback loop supported by river flooding simulations. This allowed the territorial testing of multiple design solutions in respect to the hydrological dynamics that they would create, therefore permitting a design towards the desired consequences. After the digital testing phase, a landforming intervention was proposed to guide the expansion of the river over the years into a shallow wide marshland, mitigating flood risk and placing the first stone to improve biodiversity in the selected locations. (Figure 7).

Fig. 7 Data-design feedback through river flooding simulations. Alzette 2.0 River Re-visioning. Developed by students Leyla Saadi, Marta Maria Galdys, Sridhar Subramani, Ivan Reyes Cano. Master in City & Technology, IAAC, Barcelona, 2021.

Finally, the riverbank proposal alongside its constituent flooding simulations is used as a base to inform a participatory process for the co-design and co-management of a bioremediation forest, crucial for the functional integration of the river within the surrounding ecosystem. Primarily planned to clean the soil and the water from the heavy metals it carries, the forest becomes an opportunity to positively engage with the local communities on site through a simple digital platform. Through this participatory process, the forest would eventually provide a new source of income for those affected the most, while diversifying the economy of the area; integrating anthropogenic interests and non-human forces within the long-lasting renaturation process.

Conclusions

Through the methodology presented we can begin to unpack the complexity related to understanding ecological and morphological connectivity, and its potential to further empower these environmental systems. Ecological connectivity, being a global priority for preserving biodiversity and ecosystem functions (IUCN, 2017), underlines the interest in empowering designers with a set of new tools and analytical processes to understand and represent these conditions in order to create new landscapes that embed nature, and its dynamics, as an active partner.[9] In doing so, we are enabled to reconsider the polarisation between environmental forces and anthropocentric ones, with the finality of providing an opportunity to use this as the basis to design cities consciously for, and within, climate change adaptation. In this sense, today's digital culture provides an interesting platform to facilitate the operability of this paradigm shift in terms of urban planning and design, by embedding data driven approaches – computational modelling, data analytics, simulation, and more – into the analytical and design pipeline, taking advantage of the large availability of datasets, often accessible as open data. On a broader scale, this opens opportunities to rethink the potentials and responsibility of design, enabling it to respond in an informed manner, and in line with the New European Bauhaus initiative, opening a new space of reflection in the fields of architecture and urbanism, with a focus on sustainability, aesthetics, and inclusion.[10]

Furthermore, the approach presented directly enables a response to one of the more impending environmental challenges of today:

> The degradation, fragmentation and disconnection of natural habitats on land and in the sea ... has resulted in the alteration and isolation of habitat important for movement of organisms and for the maintenance of ecological processes present in previously connected landscapes and seascapes.[11]

9 International Union for Conservation of Nature (IUCN), 2017. https://www.iucn.org/theme/protected-areas/wcpa/what-we-do/connectivity-conservation (accessed February 2022).

10 https://europa.eu/new-european-bauhaus/index_en

11 "Frontiers 2018/19: Emerging Issues of Environmental Concern," 2019, https://wedocs.unep.org/20.500.11822/27538

This disruption presents serious threats to vital ecosystem services in both the ecological and anthropogenic spheres. We need to act and we need to do it fast. To do so, we need to reconnect habitats and prevent any further fragmentation.

By exploiting data relative to context specific ecological actors to frame the effectiveness of their ecological networks, we can combine this with the physical properties of specific metropolitan environments to evaluate connectivity towards the identification of relevant pathways for ecology to connect and thrive. This consequently provides the methodological basis and a viable approach for designers to effectively, dynamically and systemically design for ecological transition towards connected living environments.

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FlowerPowder: a new ecological corridor for pollinators, 2020/21, by students: Adriana Aguirre Such, Simone Grasso, Matteo Murat, Riccardo Palazzolo Henkes;
[ECHO]NNECT: Mutualistic symbiosis driving back nature, 2021/2022, by students: Dimitrios Lampriadis, Joseph Bou Saleh, Julia McGee, Kriti Nirmal;
Rewilding Luxembourg: A co-existence experiment with beavers as engineers and children as citizen scientists, 2020/21, by students: Alvaro Cerezo Carrizo, Arina Novikova, Dongxuan Zhu, Stefania-Maria Kousoula;
Re(naturing) BCN: future Llobregat, 2020/21, by students: Aishath Nadh Ha Naseer, Hebah Qatanany, Laura Guimaraes, Mario Jose Gonzalez, Sinay Coskun;
Alzette 2.0: River Re-visioning, 2020/21, by students: Leyla Saadi, Marta Maria Galdys, Sridhar Subramani, Ivan Reyes Cano.

Miguel Carvalhais
i2ADS & Faculty of Fine Arts,
University of Porto

Designing (with) Computational Objects

From Metamedia to Metaenvironments

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We live in a regime of computation, a post-digital condition in which we coexist with a technological unconscious that surrounds us and saturates our lives. This paper looks at how this affects us as citizens, and how it transforms our practices as designers, architects, artists, and creators of things. Informed by design, it examines how computation impacts things and spaces—from tools to media, from architecture to environments—and how its affordances breed new objects that are ontologically at odds with the non-computational things and spaces we have grown accustomed to. Through a critique of current tools built with machine learning, this paper enquires how we can negotiate authorial positions in this algorithmic world, and how working within computation reshapes the core tenets of design, or even casts a light onto what those have really been all the time.

The (Computational) World

In his 1974 book *Computer Lib/Dream Machines*, Ted Nelson hinted at the impact that computers, which were transforming into something more than mathematical tools, would have in our lives.[1] By 1974 the usage of computers was starting to broaden beyond what had been its domain in universities, large corporations, or armies, and at the dawn of personal computing, Nelson understood that this could lead the world to revolutionary transformations.

As Nelson said then, "we live in media, as fish live in water," but fifty years later, transformed by computers and computational technologies, our media are now digital, and our world is saturated with computation.[2] We live in a post-digital condition, a regime of computation in which we coexist with a technological unconscious that is formed by objects, by the software embedded in them, and by their networks, and that intersects with us in ways that are often subtle and almost unnoticeable.[3] Computation became a fundamental infrastructure of contemporary life, often mysterious due to its complexity and opacity, in spite of the quasi-permanent veneer of user-friendliness and immediacy.[4] The technological unconscious is perhaps the most salient aspect of the "massively interconnected system of technology vibrating around us," which Kevin Kelly calls the *technium* and that Manuel DeLanda, following Deleuze and Guattari, defines as the *machinic phylum*: a negentropic process of nonorganic life, self-organising processes, and flows of matter, energy, and information.[5]

The technium is an accelerant of hominisation, the process of emergence of the human, acting at the level of social organisation and in the development of physical and cognitive extensions.[6] Starting with the usage of computers as media, it is now leading to the emergence of computational spaces, as computation and computational technologies change their location and time, going from being very localised and sporadic experiences to becoming a ubiquitous and constant state.

All objects are becoming computational, in a spectrum that spans from *coded objects*, where software becomes a part of the desired performance, through *coded infrastructures*, *coded processes*, and *coded assemblages*, a range of *code/spaces* that transform "the conditions through which society, space, and time, and thus spatiality, are produced."[7] When computation becomes "mutually constituted" with our objects, spatiality, cognition, cultures, and societies, our very lives start resembling code/spaces too, i.e., objects that do not dispense with computation, and do not even function without it.[8]

And as computation becomes so enmeshed with objects, and these became difficult to individuate from computation, everything increasingly becomes — much as computation, and because of its influence — cognisant, intelligent, protean, and abstract.[9] And everything also becomes increasingly hackable, unstable, unsafe, adversarial,

1 Theodor H. Nelson (1974), "Computer Lib / Dream Machines," in *The New Media Reader*, ed. Noah Wardrip-Fruin and Nick Montfort (Cambridge: MIT Press, 2003), 301–38.
2 Ibid., 306.
3 Florian Cramer, "What Is 'Post-Digital'?," *A Peer-Reviewed Journal About Post-Digital Research* (2013); N. Katherine Hayles, *My Mother Was a Computer* (Chicago: University of Chicago Press, 2005); Nigel Thrift, "Remembering the Technological Unconscious by Foregrounding Knowledges of Position," *Environment and Planning D: Society and Space* 22, no. 1 (2004): 175–90.
4 Julia Velkova and Anne Kaun, "Algorithmic Resistance," in *Skin and Code*, ed. Daniel Neugebauer (Berlin: Haus der Kulturen der Welt, 2021), 57–74.
5 Kevin Kelly, *What Technology Wants* (New York: Viking, 2010); Manuel DeLanda, *War in the Age of Intelligent Machines* (New York: Zone, 1991); DeLanda, *A Thousand Years of Nonlinear History* (New York: Zone, 1997).
6 Pierre Lévy, *Collective Intelligence* (Cambridge: Perseus, 1997); Kelly, *The Inevitable* (New York: Penguin, 2016), 273.
7 We will define *objects* following object-oriented ontology, i.e., in a very "wide sense: an object is anything that cannot be entirely reduced either to the components of which it is made or to the effects that it has on other things." See Graham Harman, *Object-Oriented Ontology* (London: Pelican, 2018), 43. OOO's objects can be material or immaterial, they can be actual, virtual, even imaginary. This term will then cover tools, media, and all artifacts impacted by computation, including organisms and the contexts where they live. Rob Kitchin and Martin Dodge, *Code/Space* (Cambridge: MIT Press, 2011), 13.
8 Kitchin and Dodge, *Code/Space*, 16.
9 Hayles, *Unthought* (Chicago: University of Chicago Press, 2017).

surveillant, and discorrelated.[10] Imbued with computation and software, everything connects to our dataome and contributes to it.[11]

Computation absorbed media and gave rise to *metamedia* that have "degrees of freedom for representation and expression never before encountered" and the capacity to remediate and transform into existing media, as well as media that are yet to be invented, or are physically impossible.[12] As its impact extends to spaces, via computations embodied in robots, objects, or other automata, it gives rise to new, singular *metaspaces*. Not those of fiction, or of product pitches from technology companies, with headsets, or gloves, or low-res, low-polygon-count models.[13] Rather everything and everywhere, analogue and digital, somatic and molar, physical and immaterial, actual and virtual, *metainterfaces* or *metaenvironments* that potentially touch and include everyone.[14]

Computational Objects

Computational objects take many forms and can hardly be described in simple terms. They can be conceptualised from a set of common computational affordances, as Janet Murray did when describing them as being *procedural*, *participatory*, *spatial*, and *encyclopaedic*.[15] This set the groundwork for an ontology that is, much as the computational objects themselves, hierarchical, with procedurality taking a central place as the "defining ability to execute a series of rules."[16]

A computation is a process that follows rules that are both finite and describable.[17] These rules are usually algorithmic and formal, a principle that has been central to digital computation since it was devised by Alan Turing.[18] The realm of computational objects is not limited to digital computations and computing engines, and includes a host of other phenomena that fall under what can be described as analogue computers, or as chemical or biological systems that are able to process information and *compute*, a group that also includes humans. However, as most computational systems in the technium are digital, we will focus the discussion on those.

Because of their procedural nature, computational objects are paradoxically both deterministic and irreducible, i.e., impossible to anticipate or predict. This means that although we may know that a given computation can only converge into a single output or end state that is deterministically dictated by its rules, we may never be able to know what that state is before the computation actually reaches it.[19] At the same time, in some computations, the same deterministic end result can sometimes be arrived at through multiple causal paths, i.e., different sequences of events.[20]

Computational objects are also heavily predicated on ideas of imitation, simulation, and emulation.[21] The universal computing machine that Turing conceived is an apparatus that can read the description of another machine and start performing its operations. This means that

10 Shane Denson, *Discorrelated Images* (Durham: Duke University Press, 2020).
11 Caleb Scharf, *The Ascent of Information* (New York: Riverhead, 2021).
12 Alan Kay (1984), in Brenda Laurel, *Computers as Theatre* (Reading: Addison-Wesley, 1993).
13 Among the fictions we can include the *metaverse* of Neal Stephenson's *Snow Crash* (1992), or the *matrix* in William Gibson's *Neuromancer* (1984) or the eponymous movies. In technological products we can include Linden Lab's *Second Life* or Meta's *Horizon Worlds*.
14 Christian Ulrik Andersen and Søren Bro Pold, *The Metainterface* (Cambridge: MIT Press, 2018).
15 Janet H. Murray, *Inventing the Medium* (Cambridge: MIT Press, 2012).
16 Ian Bogost, *Unit Operations* (Cambridge: MIT Press, 2006); Murray, *Hamlet on the Holodeck* (Cambridge: MIT Press, 1997).
17 Rudy Rucker, *The Lifebox, the Seashell, and the Soul* (New York: Thunder's Mouth, 2005).
18 Alan Turing. "On Computable Numbers, with an Application to the Entscheidungsproblem" *Proceedings of the London Mathematical Society* 2, no. 43 (1936): 544–46.
19 Stephen Wolfram, *A New Kind of Science* (Champaign: Wolfram Media, 2002).
20 Idem., *A Project to Find the Fundamental Theory of Physics* (Champaign: Wolfram Media, 2020).
21 Miguel Carvalhais, *Art and Computation* (Rotterdam: V2_Publishing, 2022).

a universal computing machine can compute anything that is computable, as anything computable is the output of a machine that can be emulated by a universal machine. But by performing as another machine, a universal computer does not simply simulate or emulate it. What happens in universal computers, and in computational objects in general, is that because of the nature of the processes that are developed, we find something that is more than an emulation, more of a *recreation*. When a universal computer is programmed to *act as* another machine, it can be thought of as actually *becoming* the other machine, transforming itself into a different machine that is then able to produce new computational outputs that are identical to those produced by the original machine.

As a computation then emerges from the affordances of its physical substrate — the hardware — and its links with the rules and data that drive it — the software — it becomes something that is neither one nor the other. It becomes a new informational and causal object that is at once strictly reliant on its material and informational substrates, but also independent from them.[22] As an irreducible informational being that is structurally coupled with its context, any new computation develops a new informational pattern, a copy without an original, a *simulacrum*.[23] It is not a copy, simulation, or emulation *of* something, it *is* something.

A computation has agency, can make choices, act, and express intentions, or drives. All of these are, of course, programmed into it in one way or another, but often, we can see manifestations of a computational object's subjectivity when it turns into a black box that escapes the control of its designers and programmers.[24] Furthermore, the context with which the computational object structurally couples, includes not only any matter, energy or information that can be perceived by or acted upon, but also any number of other computational objects or organisms — including humans — that it may be able to interact with. Everyone and anything that interacts with a computation becomes part-processor and part-programmer, and all actions in this mesh of living and non-living, of natural and artificial things, become ontologically equivalent, contributing to and becoming part of the computational object.[25]

Metamedia

Computational media deeply transformed the media ecology and our aesthetic relationships.[26] Although computation had haunted media for a long time, it was only when digital computers became a universal medium, a solvent for all forms of sign production and communication, that we started breaking away from some of the paradigms that had for long shaped our culture.[27] Given a technological context with so many radically new affordances, media evolved into forms that go beyond imitation and remediation.

Computational media are outstanding remediators, that promise a transparent replacement of all media with cheaper, faster, more reliable

22 Max Tegmark, *Life 3.0* (New York: Alfred A. Knopf, 2017).

23 Hayles, "Embodied Virtuality: Or How to Put Bodies Back into the Picture," *Immersed in Technology*, eds. Mary Anne Moser and Douglas MacLeod (Cambridge: MIT Press, 1996), 1–28; Jean Baudrillard, *Simulacra and Simulation* (Ann Arbor: University of Michigan Press, 1994), 1981.

24 Alexander R. Galloway, *Uncomputable* (London: Verso, 2021).

25 Bogost, *Alien Phenomenology, or What It's Like to Be a Thing* (Minneapolis: University of Minnesota Press, 2012).

26 Matthew Fuller, *Media Ecologies* (Cambridge: MIT Press, 2005).

27 For an overview of some of these, see Carvalhais, *Artificial Aesthetics* (Porto: U. Porto Edições, 2016); Friedrich A. Kittler, "The Finiteness of Algorithms," 2007, accessed October 2022, 2018, https://archive.transmediale.de/content/the-finiteness-of-algorithms; Ed Finn, *What Algorithms Want* (Cambridge: MIT Press, 2017).

and accessible alternatives that expand what can be done with media, but also augment and transform our selves, fulfilling the utopian expectations of visionaries such as Vannevar Bush, Douglas Engelbart, or Nelson himself.[28] And computational media mostly deliver on these promises, causing a convergence of media and culture and the ongoing development of *new media* forms out of a richly generative substrate.[29]

More than any previous media forms, computational media are systemic. As Yuk Hui points out, this is not only because they are coherent but also because all media that follow them — and that are based on them — are also essentially computational.[30] The computational becomes the substrate of all media, even of those with which it does not directly intersect. By turning all information into a universal format of representation, we get Manovich's *monomedium* and Kay's *metamedium*; we get something that is amodal, endlessly transcodable, plastic, interactive and mutable.[31]

But the metamedium entails a paradox at its heart. Because it is built upon computation, it cannot avoid expressing computation in some form. Computation is transiency, action, and change; it is transformation of information rather than its preservation and stabilisation. Its very nature is in many ways antithetical to the role it is required to take on as a medium. Computations, and consequently computational media, are natural producers of information and signs, much more than their keepers.

We always expected our media to be neutral — even though we know they can never be — therefore we developed several techniques and strategies to assure that information is stable and endlessly repeatable in the metamedium. But because all information in computational media is stored in the same format and needs to be transcoded into the modalities of output that are used, all signs — letters, images, sounds, etc. — need to constantly be recreated by the medium, created anew every time they are mediated. This is a process that creates ample opportunities for the expression of computation — through phenomena such as discorrelation, glitch, or poor images — and that turns the computational medium into a space of uncertainty and performance where new signs are often created but not mediated, existing only in the liminal space of the computation itself.[32]

Amidst this, we learn to be aware of the agency of computational media, of how alien it is to humans and how it produces phenomena that although genuinely unprecedented, quickly became part of our culture and aesthetics.[33] We learn to never absolutely trust our media, to always be vigilant about their potential to drift, to mutate, to create.

Metaenvironments

Many of these considerations also extend to those objects through which computation, software, and information materialise in the world and act upon it. Whether these objects are immaterial and exclusively

28 Vannevar Bush (1945), "As We May Think," in *The New Media Reader*, eds. Noah Wardrip-Fruin and Nick Montfort (Cambridge: MIT Press, 2003), 35–47; Douglas C. Engelbart, *Augmenting Human Intellect* (Menlo Park: Stanford Research Institute, 1962); Nelson (1965), "A File Structure for the Complex, the Changing and the Indeterminate," in *The New Media Reader*, 133–146.

29 Henry Jenkins, *Convergence Culture* (New York: New York University Press, 2006, 2008); Lev Manovich, *The Language of New Media* (Cambridge: MIT Press, 2001).

30 Yuk Hui, "On the Cosmotechnical Nature of Writing," in *The New Alphabet*, ed. Bernd Scherer, 56-71 (Berlin: Haus der Kulturen der Welt, 2021).

31 Something that is not tied to specific modalities of representation, or to any type of representation at all, with perhaps the exception of the voltage fluctuations that represent bits at the level of hardware, but even those are abstract and can thus take many different forms.

32 Jordan Schonig, "Cinema's Motion Forms," (PhD Dissertation, University of Chicago, 2017); Hito Steyerl, "In Defense of the Poor Image," *E-flux*, no. 10 (2009); Rosemary Lee, "Aesthetics of Uncertainty," *xCoAx 2019*, Milan, 2019; Lee and Carvalhais, "Net Art and the Performance of Images," in *The Web that Was: Archives, Traces, Reflections* (Amsterdam: University of Amsterdam, 2019); See also Trevor Paglen's concept of the invisible image in "Operational Images," *E-flux*, no. 59 (2014), developed after Harun Farocki's discussion of operational images in "Phantom Images," *PUBLIC* 29 (2004): 12–22.

33 Denson, *Discorrelated Images*, 107.

informational, or material and physical, characteristic traits of computation get instilled into them and are often manifested.

Computation is informational, dependent on structural couplings developed through exchanges of information. With or without what we identify as *interactions*, computational objects continuously react and adjust to their environments. In this sense, computational objects are not so much what we encounter but rather what we make with them. They are dependent on feedback loops and the information exchanged is not only functional but also paramount for computational aesthetics, for the ways how we perceive and relate to computational objects. Information is what allows humans to interpret computational objects and to develop models of their causal processes, *theories of the system* that will assist them in acting together.

This makes computation performative, as it only happens when it is enacted, when its infrastructures set it in motion, and it emerges from hardware, software, and context. It is in this enactment that computation becomes, as a performative object that is not only encountered in time but is composed of time, composed of a temporal execution of code at extremely small scales, that generates what can be seen “as a new form of time,” where things are “the very medium through which time is modulated.”[34] Through this, at every step, a computation loses some futurality but this is offset by the simultaneous restarting of the computational cycle and consequent accrual of potential.[35] Thus, the coupling with a computational object is an experience of immersion in a spatiotemporal experience that requires modes of engagement that are subjective, situated, and enactive, where we explore fields of possibilities for the computational object and all the things it expands to.

Computational objects are experiential. Through their irreducibility and discorrelation, they become particulars, unique entities with which we engage as individuals, and that make us aware of the acts that are involved in their perception.[36] This engagement with computational objects is predicated on the development of theories of the system that confront our world of experience, our *Umwelt*, and make us reconceptualise it by perceiving the world through a cybernetically expanded sensorium and sharing a *technological Umwelt*.[37]

Computational objects are situated; they are concrete assemblages that exist in a specific time and space and that veer towards divergence, confronting us with events that happen to us and now. They mediate and transform our experience of space and become hybridised with our environments, combining them in ever-new ways and creating singular relationships with their inhabitants, be they organisms or other systems. They are agents, acting on and generating information. They are planes of immanence that bleed into the physical world and touch us, but that are also transformed by the relationships we develop with them. They thus function like languages and interfaces, placing us in an ergodic space of cooperation and *com-putation*.[38]

34 Ibid., 228.

35 *Futurality*, or *future future* is, for Morton, the possibility that things can come to be different, their potential for an irreducible and unpredictable to-come that characterises and realises beings. See Timothy Morton, *Being Ecological* (London: Pelican, 2018).

36 Alva Noë, *Strange Tools* (New York: Hill and Wang, 2015).

37 Lee, “The Limits of Algorithmic Perception” *Politics of the Machines: Art and After*, Copenhagen 2018. https://www.scienceopen.com/hosted-document?doi=10.14236/ewic/EVAC2018.0

38 Andersen and Pold, *The Metainterface*; Espen J. Aarseth, *Cybertext* (Baltimore: Johns Hopkins University Press, 1997). “The term computation itself comes from the Latin *computare, com-* ‘together’ and *putare* ‘to reckon, to think or to section to compare the pieces.’” David M. Berry, *The Philosophy of Software* (Basingstoke: Palgrave Macmillan, 2011), 10.

39 Harman, *Art and Objects* (Cambridge: Polity Press, 2020).

Computational objects do not encode forms and signs but rather data and rules, and their perceived stability and permanence is nothing more than a manufactured illusion. Computation is never stable, it is defined by permanent change, instability, and irreducibility. Any sign or behaviour we can perceive in a computation is continuously constructed and mediated. In computational objects, mediating is enacting, and ontology and phenomenology become entangled in ergodic acts that reveal agency. Time is not only where computation takes place but is also something that emanates from it. A computation is a succession of discrete steps that through processes of actualisation and differentiation bring a formal and algorithmic past of code into a futural *not-yet*. Because of this, morphology can never be stabilised, as that would require stopping computation and hardening a thing in its past and its appearance, not its being. Computational objects are machines of uncertainty and hermeneutics, they are gnarly systems that stand in between indeterminacy and seemingly stable configurations that are sometimes formed in fleeting pockets of reducibility.

Therefore, computational objects are highly improvisational, with their real-time events existing in a rule-bound space, and their significance depending on the exploration of its possibilities. Our interactions with computational objects are also improvisational acts, oriented to goals and tasks that are met through the engagement with a system of rules that acts as its framework but is unpredictable and forces us to improvise. They become experimental because of this uniqueness and unrepeatability. They are processes that generate action, less concerned with prescribing forms or signs but rather with creating phenomena from which forms or signs may result. They thus raise questions that can only be formulated through processes and that depend on enactment.

Computational objects are immanent, conjuring their own space and time when they are enacted and materialise. They exist across planes, and when computation stops, it does not disappear but withdraws to a space of rules, code, storage, memory, and immanence, returning whenever it is enacted again.

Through enaction, computational objects become theatrical. Computation is not formalist or literal and whenever we engage with it, we experience computational objects through mediations that demand our involvement. Computational objects are dependent of, and invested on, the circumstances in which they can engage with others, and of being encountered in a context that includes the other. This creates situations that are outside the boundaries of any of the systems and that derive their meaning from the relationships between all the engaging parts, from a theatrical enactment between the sensorial and material and the informational and computational.[39]

Computations are defining for computational objects, and if they stop, the objects change states and become something quite different.

But they do not happen in their hardware or software. Computations are not the hardware but rather how the hardware acts and processes information. They are liminal, happening in between objects and in between planes in objects. They are an abstract informational phenomenon that, although tied to physical mechanisms, is not physical itself, and exists only while it is enacted, creating a temporal space that is gone once the computation ends. Computational objects are spectral, uncanny things that fluctuate between real and unreal, hardware and software, actually and memory.

In their complexity and fleetingness, computational objects are never fully present or wholly perceivable. No single moment of a computation is the computation itself, and often there is no completion or end-state we can anticipate arriving at. Computations are objects to which we may attune, that we can discover, and with which we can collaborate. With perhaps the exception of the most simple, predictable, and reducible computations, most computational objects become "massively distributed in time and space relative to humans" and are difficult to perceive directly.[40] Their complexity and diversity can be well described by the criteria that Timothy Morton developed for *hyperobjects* such as the biosphere, planets, global warming, or other systems that are fundamentally characterised by viscosity, nonlocality, temporal undulation, phasing, and interobjectivity.[41] They are sticky and adhere to things, becoming entangled with them in irreducible and uncontrollable ways. They are perceived through local manifestations that are not the computations themselves; they are a mesh of which we, and their local manifestations, are parts. They do not need to permanently fit our four-dimensional space-time but may exist across other dimensions, spaces, and scales, and therefore phase in and out of this one. As they compute, they radiate temporality and phase in and out of forms which we can perceive. All of this happens through the development of relationships within this mesh, between objects, processes, their links, and the gaps within them. The hyperobjectual nature of computational objects dissolves causes, signs, and information that are to be found among and in-between objects, an in-between that "is not 'in' spacetime" but rather "is spacetime."[42]

Irreducibility also contributes to computational objects having a creative potential. Computational objects can explore conceptual spaces, and transform them, doing things that at the very least *seem* creative.[43] The main activity of any computation is to continuously create itself, a process during which, creativity is manifested in the changes of how objects act on their environments and on themselves.[44] The potential for creativity arises from a spectral and ecological presence that is not past (in the code), present (in the moment-to-moment actions), or future (irreducible) but that seemingly exists outside of time, hovering above the computational substrate and permanently building new relationships.

This contributes to the subjectivity of computation and computational objects. On the one hand, by witnessing action and

40 Timothy Morton, *Hyperobjects* (Minneapolis: University of Minnesota Press, 2013), 1.
41 See Morton's *Hyperobjects* and Carvalhais's *Art and Computation*.
42 Morton, *Hyperobjects*, 81.
43 Margaret A. Boden, *The Creative Mind,* second ed. (London: Routledge, 1990).
44 Joanna Zylinska, *AI Art* (Ann Arbor: Open Humanities Press, 2020).

identifying agency, we project subjectivity onto artificial systems that can behave in complex ways and cognise. On the other, any choice of behaviour of a computational object, is not, as we have seen, strictly in its past, as a mere rule encoded in software or hardware, but is rather something that happens moment to moment, that is dependent on variable contexts and that can be seen as the machine's own choice, irreducible and subjective.[45]

Aesthetics

From the affordances of computational objects arise new types of relationships with humans and other things. The aesthetic relationships with computational objects are quite different from those developed with other things, media, or tools, perhaps with the exception of those we develop with complex organisms. In these we develop procedural readings, through a computational gaze and computational interpretations.[46] These ergodic experiences allow us to discover computations, to intuit their *allegorithms* and get to know the systems intimately, to the point where the computations in computational objects, other computations that simulate them—such as the models we develop—and those computations in the broader context where both the computational objects and ourselves exist, may be indistinguishable.[47] The aesthetic relationships with computational objects are relationships of interaction, behaviour, and modelling. They are relationships of anticipation and appropriation of the computations and their multiplication through theories of the system that enact new computations that will in their turn develop relationships with us and, through us, with the environment and the computational objects. Computational aesthetics is an aesthetics of futurality, of trying to anticipate the behaviours and choices of a computation through modelling its phenomena and enacting new future futures.

Designing for the Meta-

How does such a shift in our tools, media, and environments affect how we design? Christopher Alexander stated that the "ultimate object of design is form," but what designers design nowadays are behaviours from which form and agency emerge.[48] Designers create computation; all else follows from there.

Objects and spaces are no longer static, they are actant, and thus transform the nature of design. In the early days of the metamedium, Murray discussed procedural authorship by describing the author's role as "writing the rules by which the texts appear as well as writing the texts themselves." These rules would govern the involvement of interactors and the responses from the system, "the properties of the objects and potential objects in the virtual world and the formulas for how they will relate to one another."[49] Authors would therefore create "a world of narrative possibilities," fulfilling a role comparable to that of "a choreographer who supplies the rhythms, the context, and the set of steps that will be performed," and allowing the

45 Friedrich A. Kittler, "The Artificial Intelligence of World War: Alan Turing," in *The Truth of the Technological World*, ed. Hans Ulrich Gombrecht (Stanford: Stanford University Press, 2013), 178-94.

46 Carvalhais, "Breaking the Black Box," *Artificial Intelligence and the Arts*, eds. Penousal Machado, Juan Romero and Gary Greenfield (Berlin: Springer, 2021), 347-62.

47 Galloway discusses a level of interpretation of a computational system where one allegorically internalises them with the realities of the broader context: "video games are, at their structural core, in direct synchronization with the political realities of the informatic age," which leads him to suggest that these objects are not only algorithmic but also *allegorithmic*. Galloway, *Gaming* (Minneapolis: University of Minnesota Press, 2006), 91; McKenzie Wark, *Gamer Theory* (Cambridge: Harvard University Press, 2007), 30.

48 Christopher Alexander, *Notes on the Synthesis of Form* (Cambridge: Harvard University Press, 1971), 15.

49 Murray, *Hamlet on the Holodeck*, 152.

interactor to use that repertoire "to improvise a particular dance among the many, many possible dances the author has enabled."[50]

Following an ontological understanding of computational objects, we can also consider the computational objects themselves among the dancers, and Murray's improvised dance as being mutually constituted by human and computational objects in tandem. It is more than a collaboration, it is coprocessing.[51]

Computational objects exist in a duality between their *subfaces*, that are procedural and largely hidden from view, and the sensorial *surfaces* through which they manifest to the world.[52] The surface is not itself computational, but all its signs and behaviours are driven by the subface, a black box to which we have no access but that reacts to what happens in and with the surface. Subface and surface are one, manifesting as different strata of an object. A consequence of this dual nature is that, as designers, we do not deal with static materials any more but rather with objects that cognise, that have some sort of a mind, that have drives, desires, and a psychology.[53] Objects that we can model and that also model us.[54]

These objects are autonomously intelligent, and their capacity to solve problems across different domains or to develop their own models of the world and of the things in it does not exist merely in the past, i.e., as a transfer of intelligence from designers or programmers into the systems.[55] This is a view that *good old-fashioned* approaches to artificial intelligence often espoused, when trying to formalise decision processes for complex and creative behaviours, but that both more recent approaches to modelling intelligence and cognition do not, as they are more prone to understand intelligence as an emergent process that is at once embodied and substrate independent.

So, perhaps, more than analogies with choreography, we should think about design as dramaturgy and as the creation of living structure.[56] What do we design then? We create behaviour, action, and agency, and these exist within what we can describe as a *phase-space*, a *latent space*, or even a *conceptual space*, to use a term with connections to Margaret Boden's work on creativity.[57] Whatever name we prefer, the significant characteristic of these spaces is that they are shaped by the affordances and constraints of a system and contain all of its possible states.[58] Their exploration allows the analysis of affordances and constraints, the discovery of new states within the spaces, and even the transformation of the spaces through a metamorphosis of the system.[59] Knowledge of these spaces allows the development of a perspicuous overview that translates into understanding them and the world they are a part of.[60]

This is a rather indirect way to design. Instead of making plans through self-conscious methodologies that abstract problems and solutions, the designer operates by programming. This may mean coding computational objects, interacting with them, or shaping computation by any other means. Regardless of the approach, the designer does not

50 Ibid., 153.
51 Aarseth, *Cybertext*.
52 Frieder Nake and Susanne Grabowski, "The Interface as Sign and as Aesthetic Event," in *Aesthetic Computing*, ed. Paul A. Fishwick (Cambridge: MIT Press, 2006), 53–70.
53 *Mind* can be defined, in a fundamental sense, as something whose central activity is to think, changing inputs into outputs trough informational processes. A mind is an "action noun," something that responds, transforms, acts, adapts. A mind is not a thing, but a dynamic system defined by change. For more on these definitions, on mind's embodiment across multiple systems and organisms, see Ogi Ogas and Sai Gaddam, *Journey of the Mind* (New York: W. W. Norton & Company, 2022); Psychology is defined as a set of internal states that the system may or may not be aware of but that contribute to shaping its behaviours and drives, and even, ultimately, the system itself.
54 When we develop a theory of the system of any computational object we have contact with, we model not only its surface but also its behaviours and, to a certain extent, its internal states, also developing theories about its mind and its outlook of the world, its Umwelt. See Carvalhais, *Art and Computation*.
55 As Ada Lovelace and others have suggested. See Boden, *Creative Mind*, 16.
56 Siegfried Zielinski, *Deep Time of the Media* (Cambridge: MIT Press, 2006).
57 The term *latent space* is now common in contexts related with machine learning, such as generative adversarial networks or large language models, and has been used in this context for a few decades. Herbert Franke, the early computer artist, discussed the variability of interactive art and images as the activation of different image variants and sequences that are latent images discovered by users through "something like a journey of exploration through a world an artist has designed." See "The Expanding Medium: The Future of Computer Art," *Leonardo* 20, no. 4 (1987): 335–38.
58 We can think of constraints as negative affordances, and vice versa.
59 Developing something akin to what Boden would call *transformational creativity* and building a new conceptual space that is potentially packed with new, original, and valuable states. This amounts to a transformation of the computational object into a different object by transforming the computational machine within into a new machine.
60 Alva Noë, "Experience and Experiment in Art," *Journal of Consciousness Studies* 7, no. 8–9 (2000): 123–35, 131.

shape form or space directly but rather builds rules that then breed latent spaces. Forms, if any are produced, will be found there.

The latent space will also define horizons of action and of intent for humans and any other systems that cooperate with the computational object.[61] The designer thus shapes allegorithms and traversal functions, mechanisms to explore and discover these spaces; to verify, validate, and trust them, but also to get lost in them.

Working *with* and *for* computational objects, the designer helps to develop systems that seem alive and that can sometimes even directly involve other living systems as their constituents. Thus, *life* may become something more than a metaphor to describe aspects of cognisant computational objects.

Because of this, we discover that the tools with which we work are also the object of our work, and that, furthermore, also act on us. Our tools influence our cognition and our thinking habits.[62] To paraphrase McLuhan, we shape them, and they shape us back. Computation becomes a unified substrate for everything that includes the tools with which we develop computation and the computations we develop with them. Both are equally malleable and shapeshifting; both have the potential to replace and automate our work, something that we gladly allow them to do, sometimes uncritically.

We should not forget that the potential for openness in computational objects can be narrowed by blunt tools, and that, to find value amid the vastness of these latent spaces, we need those tools to not constrain exploration or limit our expressive potential.

An interesting recent example of this phenomenon can be found in image generation systems such as DALL·E 2 or Stable Diffusion, and in how they ultimately constrain our very notion of *image*, through the imposition of a taxonomy, of conceptual models, and tools that narrow what can be made, or what can even be thought about, with them.[63] These systems are machine learning models that can generate a large array of images in a variety of styles from the interpretation of descriptions, or *prompts*, expressed in natural language. This linguistic interface is the main tool they give us access to for the exploration of their latent spaces, allowing us to prompt the system for images of, e.g., "an astronaut, riding a horse, in a photorealistic style," to directly quote one of the examples in the DALL·E 2 website.[64]

There is certainly an interesting spectacle to a computer's interpretation of a prompt and the ensuing generation of an image or set of images.[65] However, the tools that are used to conjure such images sometimes narrow a system's potential. They can make it difficult, even impossible, to express and mediate drives and needs, or to capture anything about them at all.[66] One of the reasons for this is the fact that natural language is often not a good resource to express a design problem or to describe what we are searching for in a latent space. A consequence

61 Brian Upton, *The Aesthetic of Play* (Cambridge: MIT Press, 2015).
62 Edsger W. Dijkstra, "The Humble Programmer," *Communications of the ACM* 15, no. 10 (1972): 859–66.
63 This happens even before any arbitrary limitations built upon the systems, as e.g., not generating faces for celebrities, not producing certain types of images, not responding to specific keywords, etc.
64 https://openai.com/dall-e-2/
65 Robin Sloan points to how most presentations of outputs of these systems include not only the textual or visual output but also the prompt that led to it, hypothesising that the main aesthetic pleasure in these systems does not reside in the outputs themselves but rather on the spectacle of the interpretation that is developed by the computer. See "Notes on a Genre" 2022, accessed September 2022, https://www.robinsloan.com/lab/notes-on-a-genre/
66 Sometimes they make it impossible to even articulate seemingly mundane ideas because of the origin of the datasets used, their contents, and how they were collected. These result in patterns in generated images that are caused by limitations in training data, biases in the outcomes or what Eryk Salvaggio calls "*reductive* system interventions," or *censorship*. See "How to Read an AI Image: The Datafication of a Kiss" 2022, accessed October 2022, https://cyberneticforests.substack.com/p/how-to-read-an-ai-image.

of this is what has become known as *prompt engineering*: methods that try to evoke processes by almost transmuting natural language into abstract constructions that, despite still being composed from recognisable words, start losing the resemblance to natural language.

Programming languages are of course artificial, even if they often resort to words or constructions that are shared with natural languages. They do so, however, by imposing strict specifications that lead them to be less prone to the ambiguity, vagueness, and indetermination of natural languages, to achieve preciseness through tight lexical, semantic, and grammatical control. Because of this, programming languages can be better tools than natural languages to form and explore latent spaces, and of course, no single language can be seen as the ultimate tool for all processes. A reason for this is that in these contexts, natural languages are used as interfaces between coded computational domains that may be easier to explore with artificial languages. Another is that a poetic and creative level of language that explores ambiguity and metaphor is still beyond the reach of current computational systems, and creative ambiguity is a dialectic process that requires all players to engage in it. Perhaps what designers need then, when designing computational objects, are not generic general-purpose tools, using natural or artificial languages, but rather bespoke tools that are themselves developed as part of the design process itself.

Biographies

Aleksandra Radlińska
Dr Aleksandra Radlińska is an associate professor in the Department of Civil and Environmental Engineering at Penn State. Her research focuses on developing innovative materials to enhance infrastructure durability and reduce CO_2 impact for terrestrial and extraterrestrial applications. Dr. Radlińska is the chair of ACI 565 Lunar Concrete and past chair of the American Concrete Institute (ACI) Concrete Research Council, which helps transform academic research into industrial applications (2019–2022). She also serves as an editor for the *Journal of Construction and Building Materials* (Elsevier), associate editor for the *Nature Scientific Reports,* associate editor for the *Journal of Materials in Civil Engineering* (ASCE), and associate editor for the *Journal of Sustainable Cement-Based Materials* (Taylor and Francis). Her service to the concrete industry was recognized in 2012 with the ACI Young Member Award for Professional Achievement and again in 2018 when she was named an ACI fellow.
– ORCID 0000-0002-7977-4927

Ali Memari
Dr. Memari is a professor in the Departments of Architectural Engineering and Civil and Environmental Engineering at Penn State. His recent research has focused on the introduction of sustainable material, components, systems, and construction methods for home building. Example research areas include hempcrete, cross laminated timber, use of recycled plastic in concrete, development of carbon neutral/negative concrete, development of passive house retrofit approaches, evaluation of air barrier and vapour barriers under building movement, experimental thermal resistance evaluation of building envelope systems, 3D printing of concrete and clay-based homes, development of flood resistant homes for hurricane prone coastal regions, and development of tornado resistant homes. He has

over 300 publications, including papers in journals and conference proceedings, book chapters, edited books, magazine articles, and research reports. He is currently the editor-in-chief of the ASCE *Journal of Architectural Engineering* and the chair of the biennial conference series on residential building design and construction.
— ORCID 0000–0003–1000–7129

Axel Onur Karamercan
Axel Onur Karamercan completed his PhD in philosophy at the University of Tasmania in Hobart, Australia. He spent research visits at the University of Crete in Greece (philosophy) and the University at Buffalo, SUNY (comparative literature) in the United States. He primarily specializes in Heidegger's thought of place, language, and technology, with research interests in the East-West dialogue, philosophy of education and digital humanities. His publications appeared in peer-reviewed journals such as *ISLE: Interdisciplinary Studies in Literature and Environment* (Oxford University Press), *The Journal of East Asian Philosophy* (Springer), and *Educational Philosophy and Theory* (Taylor & Francis). He is currently residing in Paris as an independent postdoctoral scholar.
— ORCID 0000–0003–1583–1520

Daniel de Souza Gonçalves
Bachelor's degree in architecture and urbanism from the University of São Paulo (2017). Undergraduate exchange student at the Illinois Institute of Technology (2015–2016). Currently enrolled in the master's in design programme at the University of São Paulo under the supervision of Dr. Paulo Eduardo Fonseca de Campos, PhD. Member of the research group DIGI-FAB – digital manufacturing technologies applied to the production of contemporary design and architecture (2020–present).
— ORCID 0000–0001–5941–8688

Daniella Naomi Yamana
Architect and urbanist, graduate from the Architecture, Urbanism and Design School of the University of São Paulo (FAUUSP). Currently studying towards a master's degree in that institution under supervision of Dr. Paulo Eduardo Fonseca de Campos, PhD. Member of the research group DIGI-FAB – digital manufacturing technologies applied to the production of contemporary design and architecture (2016–present). Undergraduate exchange student at the School of Architecture, Planning and Landscape of Newcastle University/UK (2014–2015).
— ORCID 0000–0001–7572–0457

Eduardo Rico-Carranza
Eduardo Rico is a civil engineer focused on the application of creative forms visualisation of data analytics in urban and landscape design. His current research focuses on the development of interfaces that capture design in the form of sketches as a form of survey for large-scale input in participatory processes. He is carrying out an EPSRC funded PhD in the Space Syntax department in the Bartlett School of Architecture and acts as a design consultant for Space Syntax Limited. Eduardo currently co-directs the Master in Landscape Urbanism in the Architectural Association, exploring the role of design within large landscape and environmental policy. He has extensive teaching experience in other institutions such as GSD, Bartlett and the Berlage Institute. Eduardo has experience of working in the Urban Infrastructure Team in Arup as well as an urban and landscape designer in a variety of award-winning projects with smaller firms in London.
— ORCID 0000–0001–5941–8688

Gabriela Celani
Gabriela Celani holds a BA (1989) and MSc (2007) in architecture and urban design from the University of São Paulo (USP), and a PhD (2002) in design and computation from the Massachusetts Institute of Technology (MIT). She is full professor at the School of Civil Engineering, Architecture and Urban Design at the University of Campinas (UNICAMP), Brazil, and has been a visiting scholar at Universidade de Lisboa (UL) and at MIT. She is vice-director of Plasma, UNICAMP's maker space, and director of the Center for Studies on Knowledge and Innovation-Based Urban Development (CEUCI). Her work focuses on generative design, digital fabrication, and their applications in architecture and urban design. She was vice-president of SIGraDi and is presently vice-president of CAAD Futures.
— ORCID 0000–0001–5524–4748

Gonçalo Duarte
Gonçalo Duarte is an engineer with expertise in design for additive construction and 3D concrete printing, currently pursuing a PhD in architectural engineering at The Pennsylvania State University. He hold an MSc and a BSc in civil engineering from Instituto Superior Técnico, University of Lisbon, with a specialization in structures. He is the recipient of the 2021–22 Thomas and June Beaver Award for industry-sponsored research and is one the recipients of the Portuguese 2022 FCT (Fundação para a Ciência e Tecnologia) PhD fellowships. His doctorate research focuses on developing software that assists professionals in the design for 3D concrete printing by optimizing structures to be printable and structurally stable. This works aims to help addressing the housing crisis by enhancing and facilitating the design of affordable housing solutions.
— ORCID 0000-0002-7111-0018

Iacopo Neri
Iacopo Neri's research lies at the intersection of architecture, computer science, and urban planning. Iacopo has been involved in academia since 2015, researching computational design and geospatial analysis. He has been involved in teaching activities at the University of Florence, the Polytechnic University of Milan, the École des Ponts – ParisTech, and at IAAC – Institute for Advanced Architecture of Catalonia, where he is currently faculty of computational design and member of the AAG – Advanced Architectural Group's computational design research team.
— ORCID 0000-0002-9246-6494

José P. Duarte
José P. Duarte holds a professional degree in architecture from TU Lisbon, and a master's and a PhD in design and computation from MIT. Currently, Dr. Duarte is the Stuckeman chair in design innovation and director of the Stuckeman Center for Design Computing at Penn State, where he is professor of architecture and landscape architecture, and affiliate professor of architectural engineering and engineering design. Dr. Duarte was dean of the Lisbon School of Architecture and president of eCAADe, the European association for education and research in computer-aided design. He was co-founder of Penn State's AddCon Lab and his research interests are in the use of computation to support context-sensitive design and construction. Recently, he co-edited (with Branko Kolarevic) the book Mass Customization and Design Democracy (Routledge, NY, 2019) and his team was awarded second place in the finals of the NASA 3D Printed Mars Habitat Challenge, Phase 3: On-Site Habitat Competition.
— ORCID 0000-0002-3826-3987

José Pedro Sousa
José Pedro Sousa is an Architect graduated from the Faculty of Architecture of the University of Porto (FAUP), a Master in Genetic Architectures from the International University of Catalonia (UIC), and a PhD in Architecture from the Instituto Técnico of the University of Lisbon (IST–UTL). As part of his research on the application of digital fabrication with cork in architecture, he was a Special Student at the Massachusetts Institute of Technology (MIT) and a Visiting Scholar at the University of Pennsylvania (UPenn). Having taught in the past in Barcelona (IAAC, UIC) and Coimbra (DArq), he is currently an Associate Professor at FAUP, where he founded and heads the research group at the Digital Fabrication Laboratory (DFL). In March 2021 he was appointed a member of the High-Level Roundtable of the New European Bauhaus.
— ORCID 0000-0003-0024-4622

Marcela Noronha
Marcela Noronha is currently a postdoctoral fellow at the Center for Studies on Innovation and Knowledge-Based Urban Development – CEUCI – at the University of Campinas –UNICAMP. She was a postdoctoral fellow at the Polytechnic School at the University of São Paulo. She holds a PhD in architecture, technology and city from UNICAMP (2021). Her thesis applied parametric modelling of possible scenarios to formulate, generate and evaluate the design of urban street retrofitting interventions to improve active mobility. She was a visiting scholar at the Stuckeman Center for Design Computing at Pennsylvania State University, USA. She received a

master's degree in architecture, technology and city from UNICAMP (2012), and a bachelor's degree in architecture and urbanism (2008). She has experience in the fields of architecture, urban design, urban mobility, design computing, building information modelling, historic building information modelling and city information modelling (BIM, HBIM and CIM).
– ORCID 0000-0002-1965-4990

Mathilde Marengo

Mathilde Marengo is an Australian-French-Italian PhD architect whose research focuses on the contemporary urban phenomenon, its integration with technology, and its implications on the future of our planet. Within today's critical environmental, social and economic framework, she investigates the responsibility of designers in answering these challenges through circular and metabolic design. She is head of studies, faculty and PhD supervisor at the Institute for Advanced Architecture of Catalonia's Advanced Architecture Group, an interdisciplinary research group investigating emerging technologies of information, interaction and manufacturing for the design and transformation of cities, buildings and public spaces.
– ORCID 0000-0002-6249-0960

Miguel Carvalhais

Miguel Carvalhais is an associate professor at the Design Department of the Faculty of Fine Arts, University of Porto. He researches computational art, design, and aesthetics, topics on which he authored the books *Art and Computation* in 2022 and *Artificial Aesthetics* in 2016. His practice spans from computational design to computer music, sound art, and installations. He runs the Crónica label for experimental music and sound art, and the xCoAx conference on computation, communication, aesthetics, and x. http://carvalhais.org
– ORCID 0000-0002-4880-2542

Nate Brown

Nathan Brown is an assistant professor in the Penn State Architectural Engineering Department. He is passionate about the intersection of architecture, engineering, and related disciplines, and seeks to understand how computation can facilitate more effective overlap between them. As an undergraduate at Princeton, he primarily studied structural engineering, earning a BSE in civil and environmental engineering with certificates in architecture and urban studies. He then spent five years at MIT in the digital structures research group, where he earned an S.M. and PhD in building technology. He has also worked within the structures group at BuroHappold in Boston.
– ORCID 0000-0003-1538-9787

Paulo Fonseca de Campos

Associate professor at the Architecture, Urbanism and Design School of the University of São Paulo (FAUUSP). Coordinator of the research group DIGI-FAB – digital manufacturing technologies applied to the production of contemporary design and architecture (2011–present). Visiting professor at the Department of Architecture of the University of Coimbra, Portugal (2018–2019). Visiting researcher at the School of Architecture, Planning and Landscape of Newcastle University/UK (2014–2015). Bachelor's degree in architecture and urbanism from the Pontifical Catholic University of Campinas (1981). Master's degree in civil and urban construction engineering from the Polytechnic School of the University of São Paulo (1989). PhD degree in architecture and urbanism from the University of São Paulo (2002).
– ORCID 0000-0001-9132-3072

Pedro Martins

Pedro Filipe Martins Carvalho is an architect, researcher and invited assistant professor in the Department of Architecture of the University of Coimbra, Portugal. He graduated in architecture in 2006 from the University of Coimbra and developed a professional practice, collaborating in several offices and in his own private practice. He is a PhD student at the Faculty of Architecture of the University of Porto and an external researcher with the DFL – Digital Fabrication Laboratory group, studying the integration of digital design and fabrication technologies in architecture, with an emphasis on developing robotic construction processes for non-standard concrete structures. Since 2017 he has been an invited assistant professor at the Department of Architecture of the

University of Coimbra, lecturing several curricular units in the fields of digital design and fabrication for architecture, in the Integrated Master in Architecture, the Master in Design and Multimedia and the Erasmus Joint Master in Architecture, Landscape and Archaeology.
— ORCID 0000-0001-9597-9132

Robson Canuto da Silva
Robson Canuto da Silva is an architect and planner, graduated from the Federal University of Pernambuco. Currently, he is a PhD candidate at the University of Campinas, in São Paulo. In 2020, he was visiting scholar at the Austrian Institute of Technology, in Vienna. He is the author of Parametric Urbanism: parameterizing urbanity awarded the Ex-Aequo Prize for Critical Essays in Architecture and Urban Studies by the Institute of Architects of Brazil in São Paulo.
— ORCID 0000-0002-9307-2892

Shadi Nazarian
Shadi Nazarian is an associate research professor of architecture at Penn State and a co-founder of the AddCon Lab, exploring fabrication-aware design processes based on material sciences and unique affordances of 3D concrete printing. She holds a post-professional degree in architecture from Cornell University, a professional degree in architecture, and a degree in rnvironment design from the University of Minnesota. Her engineered functionally graded materials (FGM) can be optimized and distributed precisely where structural, insulative, and optical properties are needed, to minimize number of joints, and embodied and operational energy, while enabling better performance using seamless, graded, and transitional interface conditions, unique spatial experiences, and new possibilities in industrial, and artistic applications. Nazarian co-led the Penn-State award-winning team in the NASA 3D-printed Habitat Challenge Competition, designed to create sustainable structures using in situ or recycled materials while advancing the construction industry on Earth and beyond.
— ORCID 0000-0003-2850-5273

Sven G. Bilén
Sven G. Bilén is professor of engineering design, electrical engineering, and aerospace engineering at Penn State. He has over three decades of experience designing, building, and fielding innovative systems for harsh and demanding environments—from space to the Arctic. He employs a systems design approach to ensure mission success, translating early-stage needs into verified requirements and validated deployed systems. Building on the success of the PennStateDen@Mars team in NASA's 3D-Printed Mars Habitat Challenge, Dr. Bilén co-founded the Additive Construction Laboratory (AddCon Lab) at Penn State. Employing his broad skills set, he has built satellites and satellite systems; wireless sensor networks; cognitive and software-defined radio systems; and robotic concrete printing systems. He has a strong interest in seeing technologies he has worked on and advanced within a university research environment to get “into the wild.” He is a senior member of IEEE, associate fellow of AIAA, and member of AGU, ASEE, INCOSE, and Sigma Xi.
— ORCID 0000-0002-5416-7039

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