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ON THE SHORES OF ARCHITECTURE

Computational fluid dynamics in architectural design

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Abstract. This paper explores the implications of complex geometry enabled by computational technology to architectural theory and practice. It reviews the different design paradigms engaged breaking the horizontality of the floor and ceiling or fusing them together. It argues that current advances in fluid dynamics simulations open a new frontier in the conception of the usable architectural surface, in which the architectural product is no longer a fixed object, but the interaction between a fluid, changing environment and built form. The paper presents a case study in which computational fluid dynamics are utilized to reconvert a disused breakwater into a 'blue garden'. The morphology of the breakwater and its texture are calculated to produce the conditions amiable for supporting a varied marine ecosystem, and to shape the waves to generate aesthetically meaningful sensations. The essay discusses the technical and conceptual challenges of controlling the non-linear behaviour of fluids. It then speculates on the theoretical ramifications of having the surface interact with exterior forces and the subject's imagination to produce an event enfolding in time..

Keywords. Computational fluid dynamics; curvilinear surfaces; performance design theory; habitat engineering; coastal infrastructure.

1. Introduction

Architectural theory regarding complex geometry emphasized the continuity of the space that is achieved by the unification of the wall, floor and ceiling into a singular continuous surface. The collapse of the differences between the various building elements was argued to blur the boundaries between internal spaces and between internal spaces and the exterior. The new formal world was seen as a shift to a more fluid and dynamic way of living or occupying space, and a step towards closing the gap between landscape and architectural design in terms of morphological complexity.

Architects have now had almost twenty years of experience in the design, construction, and "consumption" of computer-aided complex-geometry buildings, and it is now possible to trace the various aspects of the influence of complex forms on the architectural profession and on the way we perceive and understand architectural space. Particularly, it is possible to historicize the incorporation of curvilinear surfaces into architectural theory and practice, in order to rethink their potential for developing new design approaches. The paper begins with a critical examination of theories on curvilinear surfaces in architectural design and precedents of built projects. It focuses on the attempts to break the horizontality of the floor and ceiling. It then argues that current advances in computational design and mainly in fluid dynamic simulations open a new frontier in the conception of the architectural surface, one that is based on material and programmatic performance and subjective sensation.

This argument is put to a test in a case study in which computational fluid dynamics (CFD) are utilized to generate usable curvilinear, inclined surfaces in response to biological, aesthetic and structural performance criteria.

2. The Folded, the Fluid, and the Oblique

Curvilinear surfaces appear in modern architectural discourse prior to the emergence of computer tools that make them possible. This section examines the evolution of these theories from their initial formulation in the theory of the Oblique, to later efforts to establish a rational and motivation for fully incorporating them into architectural design.

In the late 1950s Paul Virilio had argued that the increasingly dynamic nature of modern life was to be matched with a new way for articulating architectural spaces. In Virilio's tripartite model of architectural evolution, the horizontal order typified the agricultural era and its rural habitat. The stage of the vertical order corresponded with the industrial era. The next logical step would be the OBLIQUE order of the post industrial age (Parent and Virilio 2004). To achieve this, he argued, it was necessary to discard the notion of the vertical enclosure, whose walls are made inaccessible by gravity, and to define habitable space by means of accessible inclined planes, thereby increasing usable surface area. As opposed to metaphoric approaches to motion promoted in the 1950s and 1960s by architects such as Eero Saarinen, Virilio's approach suggests a sensual, not visual, feeling of motion.

Virilio tried to develop technical research into the "organization and the precise morphology of oblique volumes", but after few years of "overwhelming difficulties of building an oblique habitat," he decided to abandon this work. Today, however, some of the technical difficulties mentioned by Virilio have probably been overcome, and as the information technology (IT) revolution is making our lives increasingly dynamic, we are in the position to re-examine the validity of the oblique theory.

At the early phase of assimilation of computers for design in the 1980s, architects started experimenting with complex geometry in design and manufacturing on grounds other than need. One of the leading theories of complex geometry in architecture was developed by Greg Lynn. In his seminal texts "The Folded, the Pliant and the Supple" and "Differential Gravities" (2004), Lynn argues for a need for a shift from the idea that buildings must literally stand up to gravity. He offers a folded, curvilinear formal architectural morphology in which "connections by vicissitude develop identity through the exploitation of local adjacencies and their affiliations with external forces" (2004). Lynn reasoned that folded curvilinear forms arise from the incorporation of external influences, but did not define either the exact nature of these forces or the way in which they influenced architectural form. Lynn's theory treats external and interior space in a similar fashion. In fact he claims that the fold unites exteriority and interiority into a single viscous space. Like Virilio, he calls for dynamic, non-orthogonal internal spaces. Lynn evokes the burrow, which he defined as a "field of potential spaces", as an example for this type of space. But the quality or the usability of this type of space is not discussed: the mole's hill contains only space for movement.

3. Complex Geometry in usable surfaces

Since the early 1990s folded and oblique floor surfaces can also be found in built projects. Examining these projects one can distinguish between three main approaches towards the articulation of the curvilinear or oblique floor surfaces. In the first approach the inclined or curvilinear floor surfaces are merged with the wall and ceiling to form a single continuous surface. Early examples of this type are the Educatorium center at the University of Utrecht by OMA (1997), and Zaha Hadid's Contemporary Arts Center in Cincinnati (2003). In these projects, folded surfaces seem to be used to achieve a perceptual effect. This is clearly related to the more traditional image-based approaches to performance in architectural design that concentrate on the architectural object rather the human subject.

In the second approach, form is articulated in relation to the human subject. It draws on the notion that the experience of space is ultimately dependent on the actions of the human body. This approach emphasizes the tactile nature of surfaces and thus is oriented both toward the human body (senses) and the human eye (perception) to initiate a more direct and visceral experience than vision. If we exclude pavilions, exhibitions and other spaces that are either temporary or experimental, such as NOX's Water Pavilion (1997), the number of realized buildings with curvilinear or oblique floors is rather small. Moreover, within this group one can hardly find even a single example in which it entails a new type of program that is related to the IT revolution. In the vast majority of these buildings, such as the VPRO Broadcasting Company by MVRDV (1997) or the Yokohama International Port Terminal by Foreign Office Architecture (1995-2002), the oblique floor spaces are still intended to be used for circulation or for symbolic and perceptual effects rather than suggesting a new approach for occupying space.

The third approach is grounded on the idea of performance or performalism (Grobman and Neuman 2011). It is a generative approach in which the architectural form is created directly from empirical performance parameters such as radiation structure or usage. The architectural form in this case is animated since the notion of performance involves time as a parameter of design. It suggests breaking the dichotomies between the performance of the form of the object and the performance of the human subject.

While performance is often used to generate the building's envelope, it is more difficult to apply it to interiors or usable surfaces. One of the main challenges is the interrelations between various levels, since a complex geometry floor surface on one level is the ceiling of another. However, when it comes to architectural and landscape projects that comprise of one or two levels this approach could have a great potential.

4. Case study

The following section presents our case study for examining the utilization of CFD for designing curvilinear surfaces according to performance criteria. In distinction with other recent experiments in using CFD to design architectural space according to optimal performance airflow criteria (Kaijima et al. 2013), our project is based on the interaction of surfaces with water flows such as sea waves. In distinction with surfaces designed in accordance with airflow performance criteria, those designed to interact with water are usable by human agents, and may inform new ways of occupying space. Secondly, the motion of waves is easily perceptible, and unlike airflow, is pregnant with cultural signification and could readily be experienced as an aesthetic and sensuous phenomena for contemplation by the human subject. This section will elaborate on the steps taken to develop a design methodology for using CFD to optimize the engineering and aesthetic performance of coastal infrastructure. The project will be discussed in relation to the broader debate over the utility of computation simulation versus physical testing of scaled models, an issue that arises with dynamic systems that are inherently non-linear and unstable. Lastly, the paper will assess the theoretical contribution of the project to the architectural debate over performance and computer generated complex geometry.

4.1. FROM BROWNFIELD TO BLUEFIELD

The project, a seafront promenade, was commissioned by the Tel Aviv Municipality in 2013. The mile long site was used as a dumping ground for excavated material from an adjacent high-rise development and the demolition of a nearby slum. At a later date it was turned into a landscaped park, which necessitated the construction of a breakwater to stabilize the landfill. During the last decade, most of Tel Aviv's seafront has been transformed into a popular promenade, but this specific area is considered difficult to revive due to the method in which the breakwater was constructed. First, it acts as a barrier, blocking access to the sea. Second, due to the type of concrete that was used at the time, mostly invasive species are using it as their habitat. In fact, the site can be regarded as a brownfield. Since it is not possible to restore the site to its pristine sandy condition by removing the breakwater, we propose to transform it into an ecologically and socially active 'bluefield'.

Breakwaters and other types of coastal infrastructure such as piers have predominantly been designed according to the single functional criterion of countering natural forces to attain structural stability. Thus their design is defensive and reactive, and often precludes other types of uses and users. As an alternative to the single use paradigm, the project advocates an ecological, science-based and civic approach to design that meets the needs of many stakeholders, both human and non-human. To create an accessible and publically appealing environment, we are offering to integrate into the breakwater a new kind of hybrid environment we call the 'blue garden': a landscape composed of marine life, waves, marine geysers, pools, concrete surfaces and paths. It will offer active-use features such as a wet promenade, tidal and paddling pools for children, educational hotspots for learning about marine life, and places for contemplation.

The design of the artificial beach is based on three parameters that all have morphological and material dimensions, hence relevant to the subject of parametric design and complex geometry: containing the destructive forces of sea currents and waves, creating a thriving biozone for marine life, and shaping the interaction of between sea and land to generate an aesthetic experience. The following sections will examine in depth the design implications of addressing last two parameters.

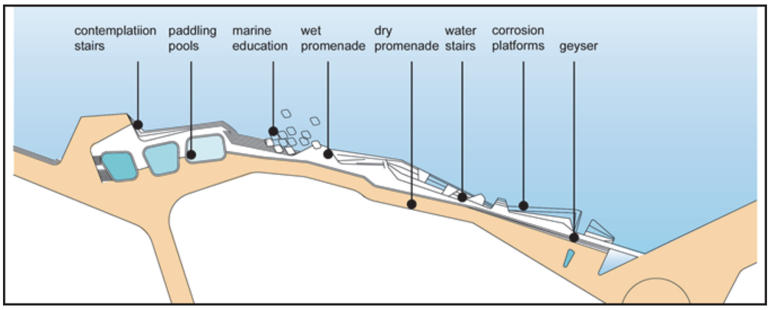

Figure 1: Site plan with proposed artificial beach and wet promenade

4.2. PARAMETERS FOR DESIGNING ARTIFICIAL BIOZONES

Most urban and industrial coastal environments are considered as sacrificed zones in relation to environmental activity. In the last few years, a different approach has been emerging that utilizes principles of ecological engineering for enhancing the biological and ecological value of coastal infrastructure, transforming them into ecosystem service providers (Chapman and Underwood 2011). Two promising approaches for enhancing coastal biodiversity, which have architectural implications, focus on the morphological and material properties of engineering elements. Increasing the texture density of the surface is one parameter that raises the potential for sustaining more abundant and diverse natural assemblages, as smooth surfaces are found to reduce the complexity of marine ecosystems (Wiecek, 2009). Studies of territorial behaviour of marine life indicate that they are also sensitive to morphology: cavities of a certain size and depth are attractive habitats for specific fish species. Thus texture could be considered as a performance parameter for enhancing the habitability of the artificial seashore.

In parallel with texture, the inclination of the elements is found to be a significant factor for shallow water habitat formation. Vertical elements tend to reduce marine diversity, while inclined surfaces, by increasing the area with a favourable combination of sunlight, moisture, oxygen and flow of nutrients, are more hospitable for marine life. Thus the performance of marine structures as biological habitats could be stated in terms of variables such as water flow, light penetration, and oxygen levels. Once fed into the design, these parameters find their optimal realization in the form of inclined surfaces with complex geometry.

Another level of complexity to consider for habitat formation is material rather than morphological. Concrete's high alkaline value exerts a negative impact on marine flora and fauna. Bio-engineers are currently developing new types of ecologically active construction materials such as ECO-ncrete, whose chemical composition is modified to enhance rather than inhibit marine life (Perkol-Finkel and Sella, 2013).

This technology will be used in the 'blue garden' in those places where the growth of marine life is desired. Furthermore, it is possible to program into the design the inevitable process of corrosion typical of coastal conditions, a problem amplified by the anticipated increase in sea levels and storm intensity due to global warming. Rather than add mass as a defensive mechanism as is currently done, it may be more sustainable to utilize the biogenic build-up capacity of local species such as oysters, tube worm and barnacles (at the annual rate of one kg per square meter) as a strategy for naturally repairing and stabilizing the man-made structure, which will slowly evolve in time into a hybrid of artificial and biological matter.

4.3. PARAMETERS FOR WAVE FORMING

The second parameter for design is the shaping of waves as an active element of the blue garden. Breakwaters are designed to deflect or dissipate the enormous energy of waves, an approach which is inherently defensive and reactive. We are advocating an alternative approach, one that actively shapes the waves for a variety of aesthetic and programmatic purposes.

The poetic forming of waves presents a challenge for architectural design, one that is unimaginable without the availability of advanced computer technology for simulating the complex interaction between wave energy and the contour and materiality of the seafloor. Software such as SWASH (Simulating WAves till SHore), an open source program developed at Delft University of Technology, makes it possible to simulate wave packets for different seafloor sections. Moreover, it can account for the interaction between successive waves, in terms of backflows, refraction and diffraction, thus allowing to conceive the blue garden as an enfolding, rhythmic experience in time.

4.3.1. First stage: section lofting

The process of designing the solid surface in order to shape the waves and create habitat conditions hospitable to marine life is divided into two steps. In the first stage, the wave is considered as a two-dimensional problem, and is shaped through the section. A series of sections are lofted into a continuous surface and tested using CFD software. Since sea conditions are variable, we have generalized the wide spectrum of sea states into three typical conditions observed for the eastern Mediterranean coast following the WMO scale: Smooth (2), moderate (4) and rough (5). Zones designed for calm sea must also perform under rough sea conditions, and vice versa, sections designed for extreme swells must also contribute to the usability and splendour of the promenade when the sea is flat.

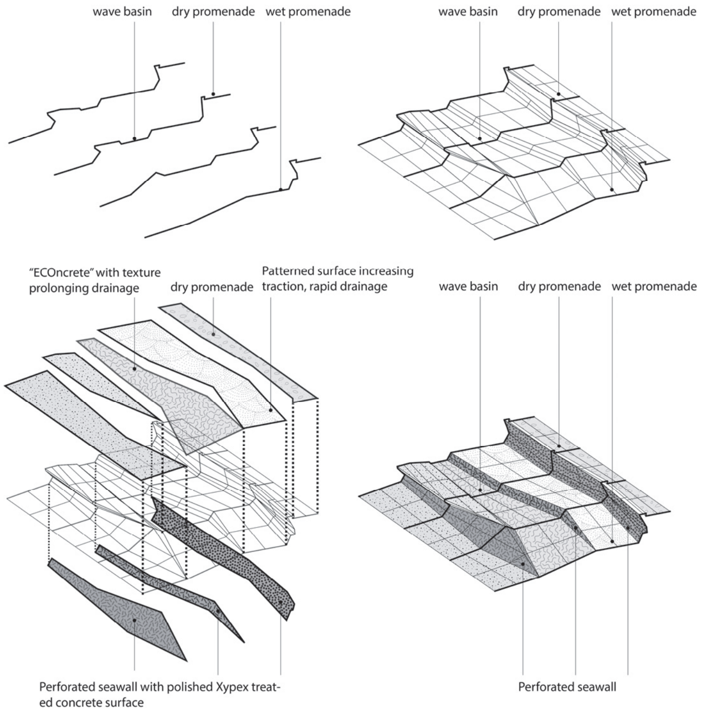

Figure 2: Design method diagram. Top left: sections according to program. Top right: section lofting. Bottom left: defining surface properties. Bottom right: output for CFD simulation.

After the initial modelling of the curvilinear surface, a second layer of texture is added to the horizontal planes in accordance with their use: those intended for pedestrians are embedded with a pattern that promotes rapid drainage and increased traction. Surfaces that are projected to support marine fauna are given a three-dimensional texture that is designed to prolong the water exchange cycle, following parameters set by the biologists.

4.3.2. Stage two: Iterative process

At the second phase the initial sections are optimized in relation to the flow generated by CFD simulation. Using an iterative process, the surface is altered and modified empirically, until an aesthetically and programmatically desirable wave formation is produced.

At this phase, a new level of complexity is introduced, that of three dimensional design. Since the behaviour of the sea is variable due to the complex interaction of changing factors such as wind, temperature, currents, and the gravitational pull of celestial objects, there is little advantage in searching for exactness and finality in planning the interaction between fluids and solid surfaces. Thus, the goal of the design process shifts from producing distinct wave forms out of the parameters generalized from the WMO scale, to generating effects out of shifts and variations between the different sea states. We are especially interested in designing elements that would force threshold behaviour, as when a wave breaks or turbulence is induced. This aim is addressed through the use of inclined, complex geometrical surfaces that are diagonal in relation to the coastline axis and tilted in relation to the sea plain, and are thus able to accommodate different patterns of wave packets and sea conditions. These surfaces are produced when successive sections are combined and rotated both horizontally and vertically, thus establishing what Stan Allen (2009, p. 218) has defined as a field condition, where "overall shape and extent are highly fluid… defined not by overarching geometrical schemas but by intricate local connections."

4.4. BOUNDARIES OF CFD

This project is currently situated at the limits of computational and building technologies. Waves are typified by threshold behaviour and are inherently non-linear, hence their exact form cannot be determined, only approximated using statistical tools. As in the field of aerodynamics, where wind-tunnels are used for design despite the availability of advance computational tools, it is expedient to test the artificial beach in wave channels at different wave and wind conditions. For this purpose, we plan to use a Computer Numerical Control milling machine to fabricate a scaled test model (1:10).

While computer simulation and model testing may approximate the behaviour of fluid motion, simulating the biological performance of the artificial seafront presents a more daunting challenge, as the self-organizing capability of biological ecosystems introduce agency into the equation. It remains to be seen if the delicate, rippling effects anticipated in computer generated virtual reality, or occurring at laboratory conditions in wave basins, as well as the desired of flora and fauna ecosystem will in fact emerge when realized in 1:1 scale under outdoors conditions.

5. Conclusion

This paper presented a theoretical and methodological framework for employing computational fluid design. It used a case study to examine the utilization of morphology and materiality to enhance the biological and civic performance of coastal infrastructure.

The contribution of the project to the debate over the status of complex curvilinear surfaces resides in its emphasis on duration and interactivity, aspects that are inherent to the concept of performance. The geometry of the surfaces is derived from the performance of waves and biological agents, rather than from any formal bias that favours such shapes for their visual appeal or symbolism. Planning the duration of wave behaviour has epistemological implications for architectural design: it is no longer experienced as an image, but rather as an experience that enfold in time. This quality sets it aside from the formalist approach espoused by Lynn or Peter Eisenman (1992), for whom curved surfaces are inherently symbolic, if not literal rep-resentations of Deleuzian concepts such as the fold.

The wave and concrete surface combination is neither static nor repeatable: it produces a rhythm, a constant interplay between flux and permanence, temporality and fixed order. Thus the shape of the man-made surface is a function of the conditions amiable to life, but also an experiential and aesthetic sequence, one which in itself cannot be fully anticipated. It creates a space for the subject's active imagination, following Kant's analysis of the beauty of fire and water streams: "neither of these has beauty, but they still charm the Imagination, because they sustain its free play" (1987, p. 95). It thus realizes the potential of architecture to overcome the division between the performance of the subject and the object.

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