Proceedings of the International *fib* Symposium on Conceptual Design of Structures

SEPTEMBER 26-28, 2019

TORROJA INSTITUTE | MADRID | SPAIN

edited by Hugo Corres, Leonardo Todisco, and Corentin Fivet

fib CEB-FIP

ACHE
Asociación Española de
Ingeniería Estructural

Proceedings of the
International *fib* Symposium on Conceptual Design of Structures
held at the Torroja Institute, in Madrid, Spain
September 26-28, 2019
Edited by: Hugo Corres, Leonardo Todisco, and Corentin Fivet

Every effort has been made to ensure that all published information has been reviewed by suitably qualified professionals and that all information submitted is original, has not been published previously and is not being considered for publication elsewhere. Further, the *fib* has made every effort to ensure that any and all permissions to quote from other sources has been obtained. The editor and the publisher are not responsible for the statements or opinions expressed in this publication.

fib Proceedings are not able to, nor intended to, supplant individual training, responsibility or judgment of the user, or the supplier, of the information presented. Although the Scientific Committee did its best to ensure that all the information presented in this publication is accurate, no liability or responsibility of any kind, including liability for negligence, is accepted in this respect by the organization, its members, employees or agents.

ISSN 2617-4820
ISBN 978-2-940643-02-8

introduction

inspiration

data collection

creativity

materialization

posters

introduction

Organizing Institutions

The conference is organised by the International Federation for Structural Concrete (*fib*) and the Spanish Structural Engineering Association (ACHE).

The *fib*, Fédération internationale du béton, is a not-for-profit association formed by *42* national member groups and approximately 1000 corporate and individual members. The *fib*'s mission is to develop at an international level the study of scientific and practical matters capable of advancing the technical, economic, aesthetic and environmental performance of concrete construction.

The *fib* was formed in 1998 by the merger of the Euro-International Committee for Concrete (the CEB) and the International Federation for Pre-stressing (the FIP). These predecessor organizations existed independently since 1953 and 1952, respectively.

The Spanish Structural Engineering Association is composed of professionals interested in research and practical applications in the field of structural engineering. It was founded in 1999, under the name of the Scientific and Technical Structural Concrete Association, as a result of the merger of the Spanish Concrete Group (GEHO) and the Spanish Technical Prestressing Association.

The Spanish Structural Engineering Association is composed of professionals interested in research and practical applications in the field of structural engineering. It was founded in 1999, under the name of the Scientific and Technical Structural Concrete Association, as a result of the merger of the Spanish Concrete Group (GEHO) and the Spanish Technical Prestressing Association.

Symposium

Conceptual design plays a leading role in defining the end-performance of structures. Facing new global challenges and embracing new technological opportunities, structural designers are encouraged to develop more creativity in their projects. Each project, independently of its size, is an opportunity to create.

Creativity in conceptual design is hard to foster and share. It is not the result of a sudden moment of inspiration, but the fruit of a serious, systematic and ambitious work in the search for the most adequate solution to a given question. Conceptual design is actually rarely taught in civil engineering schools. Traditionally, and commonly to other creative fields (e.g. architecture, literature, culinary arts, painting), successful processes are context-dependent, experience-based and principle-driven. However, new training modes, deeper understanding of history, and the advent of new tools and technologies sets forth new possibilities for creative endeavours.

The *International fib Symposium on Conceptual Design of Structures* is a singular event specifically addressed to creative designers of all experience levels. The *fib — the International Federation for Structural Concrete* — is an association created in the 1950's by eminent engineers, among which are Torroja, Freyssinet, and Levi, that aims at sharing ideas to promote the use of structural concrete. This association acknowledges and has had, throughout its history, the mission to promote, communicate and teach the value of creativity in engineering. The symposium is organized together with the Spanish Association of Structural Engineering (ACHE). The Torroja Institute in Madrid, Spain, a unique blend of architecture and structure showcasing Eduardo Torroja's creativity and teaching, is the venue of the event.

Four sessions punctuate the symposium, each corresponding to a stage in the conceptual design process: INSPIRATION; DATA COLLECTION; CREATIVITY; and MATERIALIZATION. Each session is filled with a keynote lecture, plenary presentations of selected papers, an open debate with the audience, and a series of hands-on workshops leveraging state-of-the-art tools and methods.

Institutional Support

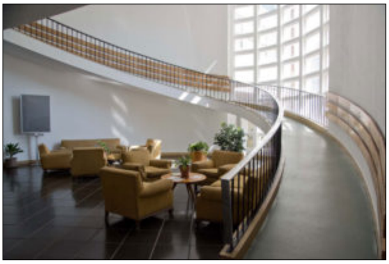
Sponsors

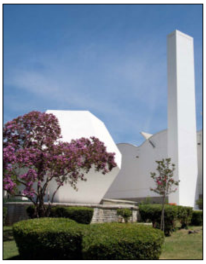
Venue

The conference will take place in the Eduardo Torroja Institute for Construction Science (IETcc).

The building ensemble was designed in 1953 by Eduardo Torroja, and represents a relevant an interesting example of his work. Among the buildings that constitute the ensemble of the institute stands out the impressive structure of the Dodecahedron coat silo, the Round canteen, the Triangulated shell roof of the testing and workshop buildings, the Pergola and the singular hanging system of the mezzanine of the main hall. Since its opening the Institute has hosted important international conferences, seminars and symposia.

Address:
Eduardo Torroja Institute for Construction Science
Serrano Galvache Street, n 4
28033 Madrid – Spain





Organizing Committee

conference chair

Hugo Corres

scientific co-chair

Leonardo Todisco

scientific co-chair

Corentin Fivet

workshop chair

Abraham Sánchez

secretary

Borja Regúlez

accounting

Héctor Bernardo Gutiérrez

media relations

Isabel Lorenzo

technical tours

Alejandro Yustres

Scientific Committee

Chair. Hugo Corres, Universidad Politécnica de Madrid, *Spain*
Scientific co-chair. Leonardo Todisco, Universidad Politécnica de Madrid, *Spain*
Scientific co-chair. Corentin Fivet, École Polytechnique Fédérale de Lausanne, *Switzerland*

Akio Kasuga, Sumitomo Mitsui Construction, *Japan*
Albert de La Fuente, Universitat Politécnica de Catalunya, *Spain*
Alejandro Bernabéu, Universidad Politécnica de Madrid, *Spain*
Alessandro Beghini, SOM, *USA*
Annette Bögle, HafenCity University Hamburg, *Germany*
Aurelio Mattoni, EPFL, *Switzerland*
Bin Zhao, Tongji University, *China*
Bruno Briseghella, Fuzhou University, *China*
Caitlin Mueller, MIT, *USA*
Carlos Lázaro Fernández, Universitat Politècnica de València, *Spain*
Dawei Zhang, Zhejiang University, *China*
Denis Zastavni, UCL, *Belgium*
Fernando Stucchi, EGT engenharia, *Brazil*
György L. Balázs, Budapest University of Technology and Economics, *Hungary*
Giuseppe Fallacara, Politecnico di Bari, *Italy*
Horacio Pieroni, Metra Ingenieros, *Argentina*
Ignacio Paya-Zaforteza, Universitat Politècnica de València, *Spain*
Jan Vitek, Metrostav, *Czech Republic*
Jiry Strasky, Strasky, Husty and Partners , *Czech Republic*
John Orr, University of Cambridge, *UK*
Jorge Bernabeu, Universidad Politécnica de Madrid, *Spain*
Jose Antonio Lozano-Galant, Universidad de Castilla La Mancha, *Spain*
Juan Jose Castellón González, ETH Zurich, *Switzerland*
Marijke Mollaert, Vrije Universiteit, *Belgium*
Mattias Schevenels, KULeuven, *Belgium*
Miguel Fernández Ruiz, EPFL, *Switzerland*
Mike Schlaich, SBP / TU Berlin, *Germany*
Mike Xie, RMIT, *Australia*
Milan Kalny, Pontex Ltd., *Czech Republic*
Olivier Baverel, Ecole de Pont ParisTech, *France*
Ornella Iuorio, University of Leeds, *UK*
Paolo Beccarelli, University of Nottingham, *UK*
Paul Gauvreau, University of Toronto, *Canada*
Pepa Cassinello, Universidad Politécnica de Madrid, *Spain*
Peter Paulik, Slovak University of Technology in Bratislava, *Slovakia*
Peter Tanner, IETCC / Cesma, *Spain*
Robby Caspeele, Ghent University, *Belgium*
Rui Póvoas, (FAUP), *Portugal*
Stein Atle Haugerud, Olav Olsen, *Norway*
Tor Ole Olsen, Olav Olsen, *Norway*

Fluid Dynamic Simulations as Conceptual Design Drivers in Shaping Architectural Structures

Jelena Milosevic

Faculty of Architecture
University of Belgrade
Bulevar kralja Aleksandra 73/II, 11000 Belgrade, Serbia

Abstract
This research is motivated by the emergent computational technologies and tools based on Fluid Dynamic Simulations that currently find their application in architecture, and particularly in the discourses of generative, digital, and performance-oriente design. The key goal is to review the potentials and constraints of performance-driven strategies that involve the assistance of these tools in shape exploration in the conceptual phase of the design process. Within the research framework of the design case studies, we obtained results that illustrate the effectiveness of the suggested approach for shaping distinctive, unconventional structural typologies with improved physical performances.

1 Introduction

This paper reports the application of design methods and computational tools based on fluid dynamic performance simulations in the design process. Motivated by the increased production of complex forms that are often nontectonic as a result of design in unconstrained CAD virtual environment, the research explores applicability of a type of physical-based simulations in production of architectural forms. Specific generative approach, employed in the research combines the use of computational algorithms for performing a particular task within the design process and designer's revision of the obtained forms and intervention, making the design result of the synergetic action of computer and designer. The assessment of this approach was carried out in the context of specific tasks, thus narrowing the research framework and performing it in particular design situations.

Starting from the hypothesis that the dynamic simulations could be used in shaping architectural structures with improved physical properties, the objective was to describe and evaluate performance-based design approach. This action-oriented design research enabled us to examine the possible way of application of digital technologies (in specific parametric modeler and soft-ware for virtual simulations), in the process of shape-finding and evaluation. Our task was to define design problems, strategy, and tools that will correspond to the set objectives. Respectively, we focused on specific design situations in which wind-load influence could be relevant for structural performances of the building and in which it could be addressed through shaping. Also, we had to choose a method that will not disturb nature of the architectural design process by subordinating it to the strictly structural performances, but that will facilitate consideration of other aspects of the architecture including functionality and aesthetics. Finally, we had to select tools that meet best the initial phase of the design process, and that enable designers to produce fast and evaluate design alternatives in a friendly environment.

A contribution of this paper is a description of an approach in which the definition and implementation of a design strategy represent part of the creative process. Contrary to the conventional practice, this process is moved form creation of a design to a definition of a more objective design tactic that encounters the needs of particular design problem-solving. The suggested approach enables avoiding preconceived solutions and psychological inertia, due to the finite experience, and facilitates exploration of physical performances and emergence of design with desirable characteristics. Besides, though the applied design research method is generally speculative, reflective, and critical in trying to learn general lessons from specific cases, the processes themselves represent experience, independently from the achievements, because they could be repeated and used in the new tasks.

2 Underlying concepts

Concepts that represent the background of the research, such as generative design, design exploration in computational environments, and performance-based design have an extensive literature.

Generative design is related to the application of artificial production systems in creative processes. These systems participate in decision-making and the designation of the final designs. Generative design discourse is inspired by instability and complexity, while methods applied in the design process are rooted in the modeling of the dynamics of the systems [1]. The generative design process is repetitive, and solutions are developed through a certain number of iterations.

Generative systems initially used in architecture were regular systems such as sets, symmetries, tessellations, number sequences, the golden ratio. Combinatorial or configuration systems such as shape grammar were particularly attractive in the 1960s, because of industrial mass production realized with computationally based rationalization, the methodology of modular coordination and constructive precision. Subsequently, post-industrialization supported by automation and digital fabrication brought aspiration for mass-customization oriented on dynamic processes and increased complexity. Digital tools enabled the application of the irregular generative systems based on the randomization, stochastics, or complex systems inspired by the emergent biological systems. Lately in generative architecture discourse work authors of which some are purely interested in the exploration of visual complexities, while others such as [2], [3], [4], [5], or [6], study processes of form-finding or morphogenesis.

Development of digital technologies influenced that their applications become dominant to the extents that currently the term generative design mainly refers to computational design. Krish [7] states: *Generative design is the transformation of computational energy that supports designer (human) in research on a larger number of design possibilities in the frame of constraints that could be modified*. The application of computational algorithms exceeds traditional CAD paradigms [8] in terms that the potential of computers is more efficiently used in the processes of design generation on an interactive basis, creating automated systems which anticipate states and respond to their conditions. The development of scripting (AutoLisp, Rhinoscript, Scriptographer, etc.) and classical (Processing, Fluxus, openFrameworks, etc.) and graphic (Max/Msp, Pure Data, Isidora, Quartz Composer, vvv, Grasshopper, Dynamo, etc.) program editors facilitated relatively simple implementation of ideas even to the designers note experienced in programming.

Generative design is also related to the discourse of *performalism* [9], [10]. The performance-based approach implies design production under the influence of external forces and factors (subjective or natural). Integration of parametric design and simulation tools in the design process promoted new rhetoric, letting the objective external information, to determine values that generate designs. Moreover, some authors [11], [12] or [13] stress the advantage of the introduction of this top-down objectivity in the design process. However, there is a criticism on claims related to the effects of the top-down objectivity of the design process, suggesting that they are exaggerated and in certain manner blur numerous and complex decisions and choices which necessarily must be made.

Design subordinated to the demands of specific criteria is a conventional approach in engineering, while architects usually use a more intuitive approach. Architects tend to rationalize form to a specific problem intuitively, and although these solutions are not entirely optimal, they improve designs to a certain extent. For example, the shape of the Eifel Tower is derived from the wind load diagram [14] or Gherkin Tower is curved and narrows to the top in order to decrease wind turbulence [15]. The distinctive approach represents the design of amorphous forms that indirectly resemble the fluid flow, and represent distinctive architectural expressions, like Opera in Harbin and Heydar Aliyev center in Baku by Zaha Hadid Architects [16]. Although these forms were not generated through fluid flow simulations, due to their forms and urban set have a smaller coefficient to the wind resistance in comparison to the conventionally shaped buildings. Computational Fluid Dynamics (CFD) simulations that are currently used in diverse engineering fields are still rarely applied in architecture and usually for sophisticated design, while testing in wind tunnels is reserved for skyscrapers and sometimes for the urban areas. Introduction of these technologies in the conceptual design could have exciting perspectives.

3 Design experiments

In order to test the effectiveness of the application of fluid dynamics simulations in the concept phase of the design process, we set two design problems:

- shape-improvement of a skyscraper structure and
- shape-finding of a spatial structure.

Shaping structure by considering wind-load influence could be relevant in both cases and contribute to the structural performances of a design proposal. The master architectural students did both designs at the Studio Design courses at the University of Belgrade – Faculty of Architecture.

The conceptual design process, in both cases, had the following phases:

- generative system creation,
- design exploration and
- design selection.

After analyzing a specific design problem, the task was to define the design procedure, described by an algorithm which was then implemented using digital tools. We decided on the approach based on designer-computer interaction, so diverse objective and subjective information was used to construct a dynamic simulation context, for form exploration, interpretation, and decision-making. Computational tools drove shape exploration, evaluation of aerodynamic performance, and informed process of design selection performed by the designer. The design process was iterative, and forms emerged gradually, through progressive adjustments and improvements. Design activity needed a precise definition of the problems to solve, in order to accurately understand relation, flows, and performances and obtain design solutions whith desirable attributes. The suggested approach enabled avoiding preconceived solutions and psychological inertia, due to the finite experience, creative methods drive designers through the problem abstraction and after through the abstraction of solution.

Designs were realized by the application of CAD and CFD software, which enabled diverse visualizations and analysis. The applied CAD system enables constraint-based modeling in which every element may be connected using parameters, relationships, and references. A specific part of the modeling process was automated. CFD tools were used to evaluate forms and to inform the process of form selection. Significant demand in choosing a CFD program was to provide an environment suitable for the concept phase of the design process, i.e., a tool that is flexible and fast. Between software/programs/plug-ins or algorithms for fluid simulations that have the potential for application in architecture, we selected Autodesk FlowDesign [17].

3.1 Design experiment 1

3.1.1 Task and process

The task was to design the structural system for the skyscraper in the New Belgrade, Serbia. Located near Riverside this skyscraper is 420m tall, and like any building of such height, it represents spatial dominate and city's landmark. Design tests approach in which aerodynamic performance considerations are included in the conception phase of the design. Wind resistance problem must be mainly addressed in tall building design, having in mind that lateral forces considerably affect these structures [18]. That is why the aerodynamic shape was an essential aspect of the design proposal.

The design process included the production of quite diverse formal proposals based on the author's ideas. Then the analysis of these designs using fast CFD simulations was done in order to learn about their aerodynamic properties and narrow the range of design solutions. In this phase study of the fluid dynamic phenomenon described in [19], [20], [21] was done. After that selected design was further gradually improved following both architectural and structural demands.

3.1.2 Materials and tools

The geometry of the structure was modeled in a NURBS based parametric CAD system Rhinoceros [22]. For the evaluation of performances, we used early mentioned software Autodesk FlowDesign. This software enabled us to run fast simulations, evaluate design proposals, improve forms based on feedback data in the iterative design process. Because of the speed, the precision and the reliance on the obtained results from FlowDesign is constrained. Also, the program is restricted to modeling properties of no other fluid than air. However, since it is used in the initial phase of the design process, these drawbacks are acceptable. FlowDesign informed us with numerical (forces and drag coefficients) and graphical (visualization of the fluid's particles around the form - vectorization of the fluid's flow and mapping of the flow speed) simulation results.

3.1.3 Results and discussion

The result of the design experiment 1 (Fig. 1) is a structure which form was a result of gradual adjustments based on simulation data done in the iterative design process. This approach resulted in the aerodynamic form, which is confirmed by reduced drag coefficients. This design confirms that the forms derived through the process informed by the fluid dynamic simulations have expected improved aerodynamic performances. These designs are not only rational from the aspect of structural performances but also have satisfying aesthetical qualities. In common practice, architectural designs may be created without considerations of aerodynamic properties. In this case, improvement of the performances, to the certain extents, could be done through post-design optimization. However, this example demonstrates the application of fluid dynamic simulation in the early design stage is towards the production of sustainable designs, which of particular importance in the case of specific structural typologies. Also, one should be aware that more precise, detailed, and time-consuming simulations would be obligatory in the further elaboration.

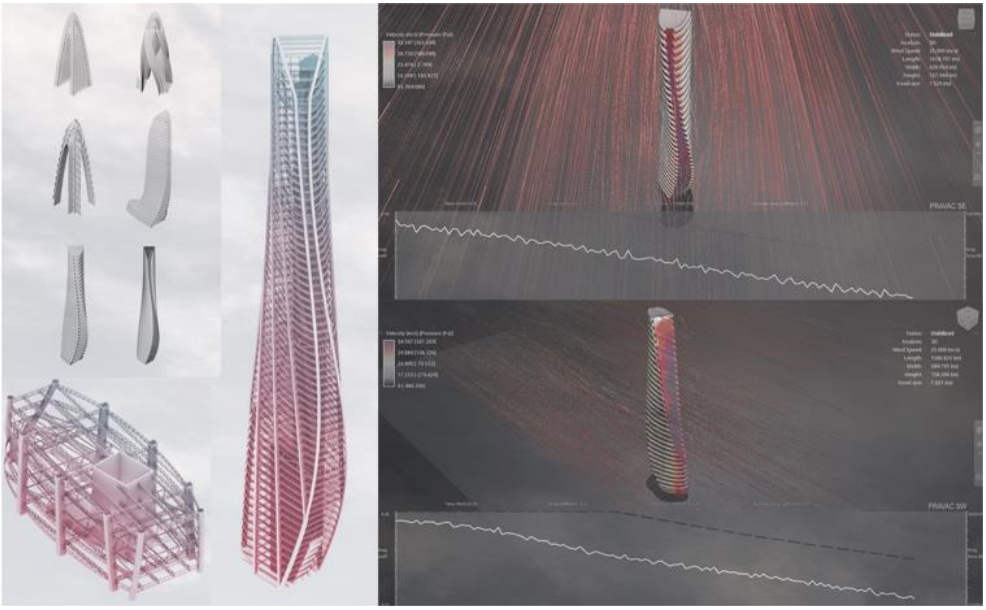


Fig. 1 Skyscraper design – alternative shape proposals in the process of form-improvement, the structural system of the building, visualization of CFD simulations in Autodesk FlowDesign (student: Savo Ukropina, mentor: doc. dr Jelena Milošević, 2018)

3.2 Design experiment 2

3.2.1 Task and process

The design task was to create a spatial structure for the nautical museum in Belgrade, Serbia. The intention was to design a floating structure located at the Danube River that will activate riverside. The structure has dimensions 40m wide, 80m long and 22.4m high, where the launch is approximately 8m, and a total surface of about 5800m2, where 3000m2 is for the exhibition. Design tests hypothesis that fluid forms conceived by applying physical laws can have good aerodynamic performances.

The design was realized through phases previously mentioned in section 3. During the creation of the generative system, much work was dedicated to the analysis and description of the physical phenomenon underlying form generation. The particle systems represented the fluid form of the structure. Once the phenomenon was abstracted, the design potentials were instrumentalized into a design explorer – an algorithm. Then, the strategies for the implementation of algorithm were revised. Considerable work was dedicated to writing a code that simulates a dynamic particle system, which generates trajectories in a controlled virtual environment, and describes volumes around obtained trajectories. The code was exploited for design exploration and production of many formal solutions. This design driver was based on physical laws that designer could modify in order to obtain forms that meet diverse design demands (such as functional or aesthetics). In the process of design selection, a number of solutions were first narrowed by using subjective aesthetic criteria and then selected designs were subjected to the fast CFD simulations in order to inform decision-making process with the aerodynamic performances of the selected forms.

3.2.2 Materials and tools

In this case, the generative system was fully parametrized, and that facilitated fast and easy manipulation and changes. For shape-finding, we used visual programming editor Grasshopper for commercial CAD software Rhinoceros [23]. For the simulation of particle systems, we used Quelea plug-in [24], and for the description of the volume, we used program code (VB script) that generates surface based on the marching cubes concept. In order to generate the diverse outline of trajectories, we used seven virtual forces, in three diverse sets for the diverse number of particles. The sets of virtual forces enabled the generation of trajectories for translator and vortex circulations of fluid. Then, for each set of particles, obtained trajectories were preserved and used for describing volumes. This framework enabled complete parametric control of shape-finding and manipulation of diverse parameters that define complex geometry enabled the emergence of numerous different designs.

For the performance evaluation, we also used Autodesk FlowDesign, and small drag coefficients were also desirable results. The FlowDesign software was used for the fast review of the air-flow around a number of forms and selection of the final solution. Nevertheless, in the phase of design development (which description is beyond the scope of this paper), aerodynamic performances of the selected solution were further analyzed using commercial Autodesk software Computational Fluid Dynamics (CFD) [25]. This software, based on the finite element method, provided us with more precise and more reliable results which were also validated by the experiment in the wind tunnel.

3.2.3 Results and discussion

Design experiment 2 (Fig. 2) confirmed that dynamic simulation tools could be used effectively in the shape-finding of spatial structures. Structures obtained from described generative design process exhibit good aerodynamic performances. Based on simulation results (numerical and graphical), it could be concluded that the structure has satisfying aerodynamic performances. Furthermore, the analysis of resistance coefficients it can be concluded that the values (from 0,26 to 0,74 for diverse simulation directions) are much smaller in comparison to the conventional cubic forms (1.17).

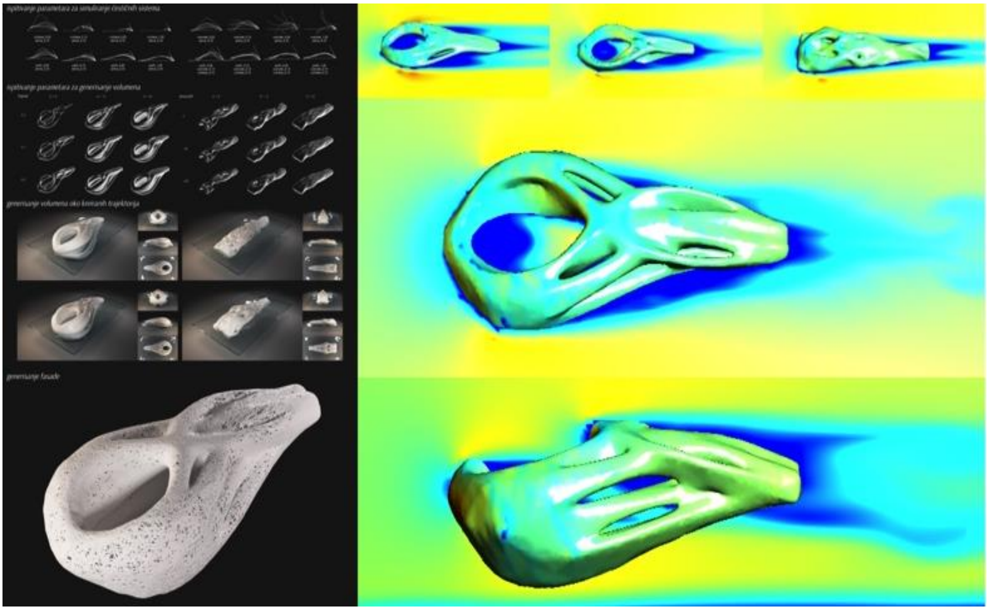


Fig. 2 Spatial structure design – alternative shape proposals in the process of shape-finding, final design, visualization of CFD simulations in Autodesk FlowDesign (student: Ognejn Graovac, mentors: prof. dr Miodrag Nestorović and doc. dr Jelena Milošević, 2018)

Like in all generative processes, the final form was not determined at the beginning, and design emerged based on an algorithm that has a certain degree of freedom in the creative process. Lack of predetermined formal solution prevented us from striving to predefined shapes and limitation they could potentially introduce in the exploration process. Interactive manipulation of parameters produced diverse shapes, enabling relatively fast exploration. In this set, the design is the result of the adequate combination of parameters, and the task of the designer, positioned between soft-control and management, is to define sets of parametric relations. Results are designs that are close to figuration and that closely build different relations within its environment.

4 Conclusion

The development of technologies for fluid dynamic simulations in terms of improving their environments and processing of a large amount of data exceeds their use as highly specialized tools and stimulates their varied applications. This paper demonstrates that fluid dynamic simulations potentially could be used in the conceptual design of structures as design drivers, contribute to the inclusion of aerodynamic performances consideration, and direct the design process towards the production of rational and interesting proposals. Also, fluid dynamic simulation should not be solely perceived as a means to intensify the form but as a vehicle to improve performance.

Two different design situations presented in this paper suggest that in conceptual design, dynamic simulations are efficient for both shape-improvement and shape-finding of diverse structural typologies. Both cases have a specific design process comprised of formulation of design inputs, the employment of transformative system, and the evaluation of the end products. Also, in both cases, the design relies on designer-computer interaction, which drives parametric digital models, fixing geometries based on simulation feedback and designer's explicit decision grounded in experience, perception, intuition, etc. In this setup computational tools are limited to specific tasks while designers simultaneously consider different design requirements and choose a design (out of the range of sub-optimal solutions) that best satisfies diverse aspects and is interesting for further elaboration.

There are various directions for further research. One could be related to the application of optimization algorithms in the process of the search for a solution. Also, the application of dynamic simulations both in optimization and in design could be considered for diverse structural typologies, and especially for those exposed to a relatively significant wind effect. Besides, fluid dynamics simulations not only provide the ability to check the aerodynamics of the form but could also inform us about the best positions for specific building's functions and elements such as wind turbines. Finally, the problem of fluid dynamics is interdisciplinary, and diverse knowledge could be included in its solution. Since scientific and professional fields are increasingly relying on digital technologies, more extensive research and applications of techniques and tools based on fluid dynamics probably could be expected in the future.

Acknowledgements

This research was supported by the Ministry of Education, Science and Technological Development of the Republic Serbia, Project No. TR36008.

References

[1] Galanter, P. 2003. “What is Generative Art? Complexity Theory as a Context for Art Theory.“ Accessed Mart 20 http://philipgalanter.com/downloads/ga2003_what_is_genart.pdf
[2] Nerdinger, W. 2005. *Frei Otto: Complete Works*. Birkhäuser Architecture.
[3] Balmond, S. 2006. “Form and Algorithm.“ *A+U architecture and urbanism*, Special issue, November 63.
[4] A/E Firms + Profiles. 2012. “Sasaki, Mutsuro – SAP / Sasaki and Partners.“ Accessed March 15 https://aefirms.wordpress.com/2011/01/27/sasaki-mutsuro-sap-sasaki-and-partners/
[5] Manges, Achim. n.d. “achimmenges.net.“ Accessed January 23 http://www.achimmenges.net
[6] Block Research Group, ETH Zurich. 2009-2019. “BRG.“ Accessed January 23 https://www.block.arch.ethz.ch/brg/
[7] Krish, S. 2013. “Generative Design.“ Accessed Jun 21 http://www.sivamkrish.com
[8] Terzidis, K. 2006. *Algorithmic Architecture.* Oxford: Elsevier, Architectural Press.
[9] Oxman, R. 2009. “Performative design: a performance-based model of digital architectural design.“ *Environment and Planning B: Planning and Design*, 36, 1026-1037.

[10] Grobman, Y. J., and Neuman, E. 2012. *Performalisam: Form and Performance in Digital Architecture*. New York: Routledge.
[11] Leach, N. 2009. “Digital Morphogenesis.” *Architectural Design*, 79 (1), 32-37.
[12] Menges, A. 2010. “Material Information: Integrating Material Characteristics and Behavior in Computation Design for Performative Wood Construction.” Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), New York, 151-158.
[13] Kilian, A. 2006. “Design Exploration through Bidirectional Modeling of Constraints.” PhD diss. Massachusetts Institute of Technology.
[14] JHU group. 2018. “Aifell Tower Loads.“ Accessed March 20 http://www.ce.jhu.edu/perspectives/studies/Eiffel%20Tower%20Files/ET_Loads.htm
[15] Bengani, V. 2018. “The Gherkin: Case Study.“ Accessed March 16 https://www.slideshare.net/VikramBengani/the-gherkin-case-study
[16] Zaha Hadid Architects. 2019. “Zaha Hadidi Architects - Archive. “ Accessed April 15 https://www.zaha-hadid.com/archive
[17] Autodesk Inc. 2019. “Flow Design.“ Accessed May 16 https://www.autodesk.com/products/flow-design/overview
[18] Sarkisian, Mark. 2012. *Designing Tall Buildings – Structure as Architecture*. Routledge.
[19] Chung, T. J. 2002. *Computational fluid dynamics.* Cambridge, New York: Cambridge University Press.
[20] Ferziger, Joel H. (2002). *Computational methods for fluid dynamics.* Berlin, New York: Springer.
[21] Aynsley, R. M. 2011. “Shape and Flow: The Essence of Architectural Aerodynamics.” *Architectural Science Review*, 42:2, 69-74.
[22] Robert McNeel & Associates. 2019. “Rhnoceros.“ Accessed January 14. https://www.rhino3d.com
[23] Davidson, Scott. 2019. “Grasshopper – Algorithmic Modeling for Rhino.“ Accessed January 14 https://www.grasshopper3d.com
[24] McNeel Europe. 2019. “Food4Rhino – Apps for Rhino and Grasshopper: Quelea – Agent-based Design for Grasshopper (by lxfschr).“ Accessed January 14 https://www.food4rhino.com/app/quelea-agent-based-design-grasshopper
[25] Autodesk Inc. 2019. “Autodesk CFD.“ Accessed February 12 https://www.autodesk.com/products/cfd/overview