CREATIVITY INSPIRED BY ANALYSIS

An algorithmic design system for designing structurally feasible façades

INÊS CAETANO[1], SARA GARCIA[2], INÊS PEREIRA[3] and
ANTÓNIO LEITÃO[4]
[1,3,4]*INESC-ID, Instituto Superior Técnico, Universidade de Lisboa*
[1,3,4]*{ines.caetano|ines.pereira|*
antonio.menezes.leitao}@tecnico.ulisboa.pt
[2]*INESC-ID*
[2]*sara.garcia@inesc-id.pt*

Abstract. Although structural performance has a crucial role in the overall design, its analysis is often postponed to later design stages. This largely occurs because analysis processes are time consuming and require the use of specific models and tools. This problem is then aggravated by the number of design variations that have to be analysed until an acceptable solution is found. However, the implementation of design changes at later stages is limited, as also is their impact on the solution's final performance. Fortunately, with algorithmic design, we can overcome these limitations, as it not only supports complex designs and facilitates design changes, but also automates the production of the specific models and their subsequent analysis and optimization. In this research we focus on buildings façades, proposing an algorithmic design system to support their design, structural analysis, and optimization.

Keywords. Performance-based Design; Algorithmic Design; Algorithmic Structural Analysis; Algorithmic Optimization; Façade Design.

1. Introduction

The architectural façade can be regarded as the building's skin as it separates the exterior from the interior spaces. Therefore, its design needs to consider several criteria, such as aesthetic, functional, structural, lighting, thermal, acoustic, and energetic. Of these requirements, structural performance plays a key role in ensuring the façade's feasibility and physical integrity, resisting to gravity, snow, wind, and seismic loads, among others. Unfortunately, only a few requirements are considered at early design stages, namely functional and aesthetical ones, being the others, including structural performance, typically postponed to later stages (Turrin et al. 2011), when the form is already delineated. This scenario largely results from the need to create specialized versions of the Design Model (DM), called the Analytical Model (AM), suiting each analysis tool; a process

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 1, 599-608. © 2020 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

that is not only time consuming, but also frequently inefficient, often involving redundant remodeling (Kolarevic 2003), and highly prone to information loss and the introduction of errors (Moon et al. 2011). To make the situation worse, this process has to be repeated every time the design changes. As a result, in practice, it is the engineers who make the AMs and, depending on the analysis results, suggest the architects the changes to the DMs. However, this back-and-forth process becomes potentially tiresome and may have costly impacts in the final design, as these changes get significantly expensive at latter stages (Anton and TĂnase 2016).

These limitations can be overcome by combining Algorithmic Design (AD) with analysis and optimization. AD uses algorithms to create and explore designs, supporting complex geometries, facilitating design changes, and automating repetitive tasks (Terzidis 2006). AD can automate the generation of AMs (Aguiar et al. 2017) by automatically repeating the analysis setup whenever a change is made to the design, while generating only the information required by the analysis tool. With AD, designers can integrate design analysis from early design stages and, thus, be aware of the design's performance, understand the impact of changes, and make more informed decisions. Moreover, at early stages, it is easier to incorporate the necessary changes to improve the design performance, allowing massive optimizations by simply making small design adjustments (Kolarevic 2003). On the other hand, AD and analysis can be coupled with optimization processes, a particularly useful combination when dealing with broad design spaces where manually analyzing all the design options becomes an unviable task. This approach follows performance-based design principles (Kolarevic 2003), in which, by considering performance criteria from early design stages, analysis is no longer a way of providing feedback, but a way of guiding the design process (Mueller 2014).

In this paper, we propose an AD System (ADS) for façade design, analysis, and optimization. The ADS contains several design strategies and algorithms suitable for multiple design scenarios and is coupled to different design and analysis tools, including a structural one. Moreover, the ADS can automatically produce with the same algorithm the DM and its corresponding AM, containing only the information needed for each specific analysis, updating both whenever the algorithm is changed. We evaluate the ADS in the design exploration, analysis, and optimization of a case study, a metal truss-like façade with glass panels. To this end, we use the AD tool *Khepri* and we take advantage of its portability between multiple design and analysis tools, in this case, between *AutoCAD* and *Robot*. The ADS presents the obtained results numerically and graphically, revealing the impact of changes in both the behavior and weight of the structure. In the end, the case study proves the ADS ability to produce and analyze different design variations, and to perform optimization processes by considering goals like structural performance and cost reduction, as in this case.

2. Related Work

2.1. STRUCTURAL ANALYSIS TOOLS

There are several analysis tools that simulate the behavior of a design in a real-world environment, while considering different criteria. Compared to manual analysis processes, these tools allow the automation of extensive calculations, speeding-up and improving the accuracy of performance evaluations. Also, these tools present the analysis results visually, making their understanding easier for designers, which therefore promotes a more conscientious qualitative appreciation of the results (Kolarevic 2003). Moreover, they also allow the analysis of buildings with more complex shapes, whose design and construction would be too laborious or even impossible with traditional methods (Mitchell 1998). Regarding structural analysis, we can find tools like *Robot*, *Tekla Structures*, *SAP2000*, *ETABS*, and *GSA Analysis*. A comparative study of these tools can be found in (Aguiar 2018).

However, analysis tools are not yet well-correlated with modeling tools, not only having a limited modeling capacity, but also requiring the introduction of extra set-up information, like materials and applied forces (Lee et al. 2015), which makes their use less suitable for conceptual design stages. Moreover, AMs often lack parametric features, which results in costly design changes and in the redoing of the analysis setup.

We can overcome these drawbacks by combining AD and structural analysis tools. *Karamba* (a structural analysis plugin for *Grasshopper*), *Geometry Gym* (a plugin to connect *Karamba* with *Robot*), and *GH2Robot* (a plugin to export *Grasshopper* models to *Robot*) are examples of such combination. Unfortunately, these tools do not easily automate the analysis setup, therefore hardly supporting multiple analyses (Aguiar 2018). Another drawback results from the scalability issues of the visual programming language used, i.e., *Grasshopper* (Leitão and Santos 2011), which hinders the analysis of more complex designs.

Textual programming languages (TPLs) do not suffer from scalability issues and are more flexible regarding the automation of different tasks. In this paper, we use the AD tool *Khepri*, which uses a TPL and is capable of generating, from the same algorithm, equivalent models in CAD and BIM tools. Moreover, it can also generate different AMs suiting the requirements of the supported analysis tools. As a result, it more easily handles the automation of single- and multiple-analysis processes, returning the results either graphically, in a modeling tool, or numerically, in a spreadsheet. Finally, *Khepri* can take advantage of the many optimization libraries that are available (Leitão et al. 2018), making it possible to automatically optimize designs according to multiple criteria. Differently from other well-established tools, *Khepri* is still being developed but it already supports all the features needed for the presented research.

2.2. FAÇADE STRUCTURAL ANALYSIS

AD and structural analysis are being increasingly applied in façades, whether they have visible structural elements (e.g., the diagrids systems of the *Hearst Tower* by Norman Foster and the *Morpheus Hotel* by Zaha Hadid), or not (e.g., the *Museu Soumaya* by FR-EE and the *Water Cube* by PTW Architects). We can find several studies on this topic, namely the design curvature analysis of the *Museu Soumaya* (Sidelko 2013), the energy efficiency analysis of the *Institut du Monde Arabe* (Martinho et al. 2019), and the lighting analysis of the *Astana National Library* (Leitão et al. 2017). Regarding structural algorithmic analysis of façades, recent researches evidence the advantages of this approach, although not fully automating the analysis process: in the *Beijing Greenland Center*, even though the analysis and optimization processes of the origami façade used *Grasshopper* and *ANSYS* to produce a façade using 10% less material, these tools were used independently (Schultz and Katz 2018); Herr et al. (2018) used the *Grasshopper*'s plugin *Millipede* to algorithmically analyze the wool thread-inspired façade, however, they confirmed the results separately using *Oasis GSA Suite*.

3. Methodology

3.1. WORKFLOW

The proposed ADS follows the workflow of Figure 1, which comprises the following steps: the designer develops an algorithm (A1), obtaining a design space (A2); this algorithm can generate designs in both CAD/BIM tools (B1), providing visual feedback to the designer (B2), or in an analysis tool to be automatically evaluated (C1). The analysis results can be returned by the algorithm (C2) and/or displayed in the modeling tool (C3), as well as used for optimization processes (D1), which require the production of multiple design variations (D2) to achieve an optimized design space (D3). Finally, the architect is presented with the set of acceptable design solutions, from which he then chooses the final design solution (E). To test this workflow, we develop a case study using the AD tool *Khepri*, the modeling tool *AutoCAD*, and the structural analysis tool *Robot*.

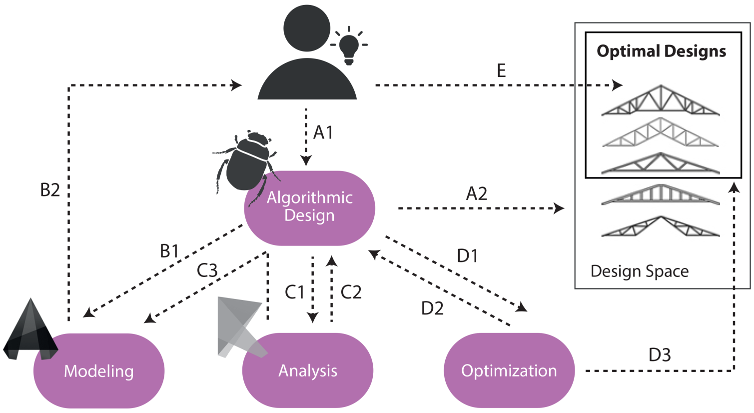


Figure 1. Workflow diagram: the designer creates an algorithm using Khepri (A1) and obtains a design space (A2); the designer uses AutoCAD (B1) to obtain visual feedback (B2) and Robot (C1) to analyze the design, receiving the results algorithmically (C2) and/or visually in the modeling tool (C3); to optimize the design (D1), the designer automates several analyses (D2), achieving a set of optimal solutions (D3) from which he then selects the final one (E).

3.2. CASE STUDY

The case study is the headquarters of the company *Channoine Cosmetics AG*, located in Vaduz, Liechtenstein, which was designed by Matthias Müller and engineered by Roschmann GMBH in 2009. The three-story building is about 15 meters high and has a rectangular cuboid shape. It has a double-skin façade, being the inner layer composed of aluminum and triple-glazed glass windows, and the outer layer made of a truss-like structure composed of stainless steel T-profiles and single-glazed glass panels. The truss-like structure forms asymmetrical rectangular pyramids, which have three of the four triangular faces subdivided (Figure 2). The heating and ventilation of the intermediate space between the layers helps the façade to be energy efficient.

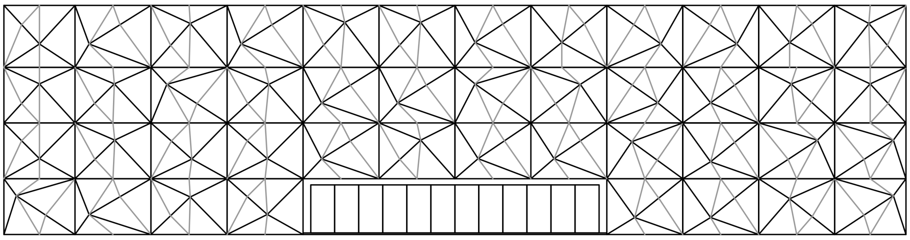


Figure 2. Front elevation (west façade) of the headquarters of Channoine Cosmetics AG (in grey: pyramid's subdivisions).

4. Evaluation

For the evaluation phase, we used the ADS to produce an AD model incorporating both the geometric and structural information of the case study, namely the buildings' overall dimensions, the floors' height, the material, height, and section radius of the truss pyramids, as well as the number of their subdivisions.

The use of structural analysis at early design stages allows the architect to be informed about the tendency his design has to deform under certain loads. We state that having a high degree of precision at these stages is not critical, as the design is still under development with many of its parameters ill-defined; a higher accuracy degree can be easily defined by engineers in latter stages of the design process. Therefore, we selected default materials (e.g., steel) and profiles (e.g., round) for the structural analysis of our case study.

Our ADS frees the designer from ensuring that the information described in the algorithm matches the requirements of both the design and analysis tools: while the geometrical model uses cylinders and spheres to represent the truss, the structural model uses a graph containing only the truss edges and vertices. Moreover, beyond geometric information, the ADS also adds to the algorithm the necessary data to setup the analysis, namely material properties, applied loads, and type of supports (fixed or non-fixed nodes). We applied two kinds of loads to each truss node, namely gravitational loads acting vertically, which are automatically calculated from the structure's self-weight, and wind loads acting horizontally.

Then, we produced several design variations of the case study and we analyzed their structural performance under identical loads. In this paper, we present eight of the examples explored using the ADS: the original truss structure with and without panel subdivisions (Designs A and B); the same truss structure but with bigger pyramids either randomly ranging their height from 1 to 4 times the original value (Design C) or doubling the size of their base (Design D); the truss with fixed-nodes only in its outer frame (Design E), with truss bars of smaller sections (Design F), with increased loads (Design G), and with a different material (Design H).

These variations resulted in design solutions with different amounts of material and therefore different weight and costs (e.g. Designs B and F), levels of natural daylight (e.g. Designs B and D), appearances (e.g. Designs C and H), and functional spaces (e.g. a double-height story in Design D, and a tall atrium in Design E). Figure 3 shows the Designs A, D, and H.

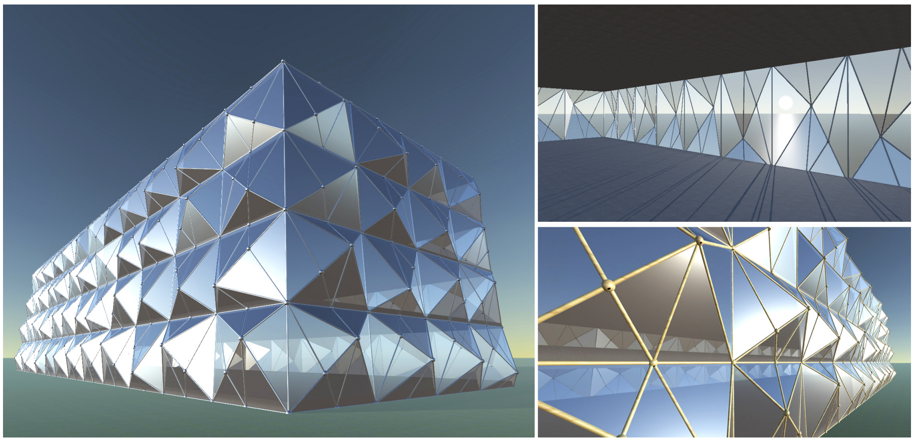
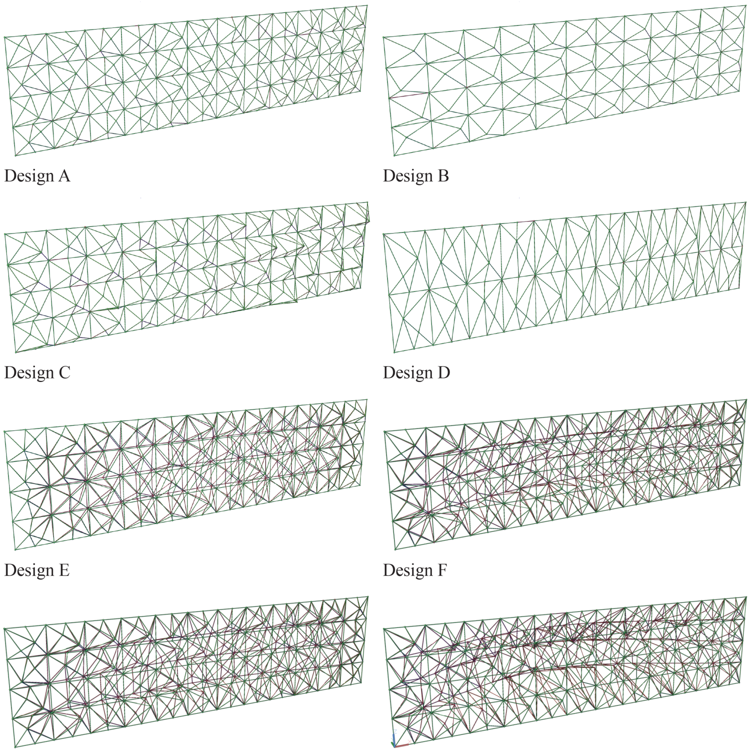


Figure 3. Renders of Design A (left), Design D (top right) and Design H (bottom right).

5. Results

The ADS presents the structural analysis results in two ways: (1) qualitative results, showing both the original and deflected structures in the CAD tool (Figure 4), and (2) quantitative results, returning the structure displacement and other structure-related information, including the bars' total weight (Table 1).

The analyses showed that the original truss structure (Design A) had little deformation, however, the solution without panels subdivisions (Design B) proved to improve the truss structural performance. Design C also revealed slight structural improvements, although the structure weight has also increased. Design D showed a slightly bigger structure deformation but a smaller weight. Design E evidenced a clear higher buckling, probably resulting from the removal of fixed supports, a scenario that was heavily aggravated with Design F. In Design G, the applied loads and, consequently, the structure's displacement doubled, but the solution with the worst structural performance was Design H, which used bamboo as material and truss bars with an increased section.



Design A

Design B

Design C

Design D

Design E

Design F

Design G

Design H

Figure 4. Designs A-H maximum displacement (in green: the original structure; in red: the deflected structure).

Table 1. Maximum displacement and bar weight of Designs A-H.

Design	**Variation**	**Max. Displacement (m)**	**Max. Displacement (relative)**	**Bar Weight (Kg)**	**Bar Weight (relative)**
A	Original case study	0.0017	0	4366	0
B	Remove subdivision elements	0.0005	-0.0012	3130	-1236
C	Pyramid's height [1.00,4.00]	0.0012	-0.0005	5125	+759
D	Double the floor's height	0.0068	+0.0051	3338	-1028
E	Remove inner fixed nodes	1.6633	+1.6616	4366	0
F	Halve the section radius in E	6.6975	+6.6958	1091	-3275
G	Double the load in E	3.3262	+3.3245	4366	0
H	Switch steel to bamboo in E	15.1506	+15.1489	4702	+336

To get a better perception of the deflection effects on the structure analyzed, the ADS provides the architect an animation of the structure displacement evolution by gradually increasing the applied loads: Figure 5 shows three animation frames of the structural analysis of Design E, with the loads increasing from 0 to 200%.

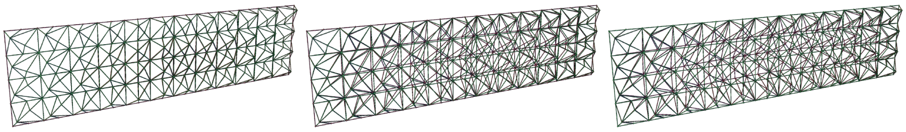
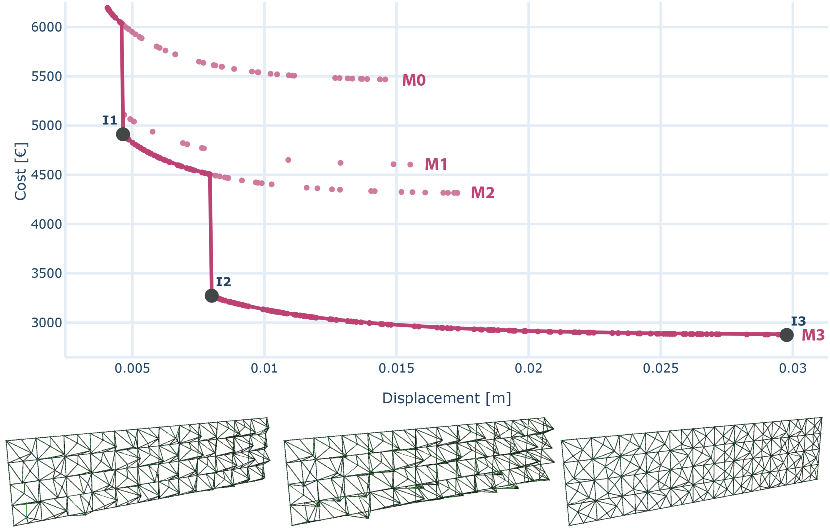


Figure 5. Three animation frames of the analysis of Design E, increasing the load from 0 to 200% (in green: the original structure; in red: the deflected structure).

We used the ADS to automate the structural analysis process and considered two goals: reduce both the structure displacement and cost, while experimenting four different materials (from M0 to M3). From the optimization algorithms available in *Khepri*, we selected the NSGA-II because it is commonly used in architectural problems, showing promising results (Belém and Leitão 2019). Figure 6 shows the Pareto front (i.e., the set of optimal solutions representing the trade-offs between the objectives) resulting from this optimization and three optimal designs, whose quantitative results are displayed in Table 2. Compared to the original truss, the results show that, to significantly improve the solution's structural performance, we need to select a more expensive material. Still, based on the Pareto front solutions, we can choose solutions in which the structural performance is slightly lower but have a much more acceptable cost. Note that, while in the previous analyses the parameters were set manually by the designer; with the ADS, they were automatically found by the optimization algorithm.



Design I1 Design I2 Design I3

Figure 6. Optimization of Design I: Pareto front (above) and three optimal designs (below).

Table 2. Maximum displacement and bar weight of Designs I1-I3.

Design	**Variation**	**Max. Displacement (m)**	**Max. Displacement (relative)**	**Bar Weight (Kg)**	**Bar Weight (relative)**
I1	Pyramid's height 5.97, M2	0.0047	+0.0030	7700	+3334
I2	Pyramid's height 5.94, M3	0.0080	+0.0063	7676	+3310
I3	Pyramid's height 0.30, M3	0.0298	+0.0281	4183	-183

6. Conclusion

In this paper, we presented an Algorithmic Design System (ADS) for façade design, analysis, and optimization, and we focused on structural performance. The ADS allows the incorporation of structural analysis at early design stages, where changes in the design are easier, faster, and cheaper. Moreover, it allows architects to be more aware of how physical objects react to forces, promoting more informed design decisions, as well as to consider more unconventional designs that may have a good structural performance.

We evaluated the ADS with *Khepri*, an AD tool that, using the same algorithm, generates both geometric and analytical models, in the development of a case study: a pyramidal truss structure façade. We applied several design variations to the original truss by considering different criteria, namely structural, functional, and aesthetic. The analyses results considered for the evaluation were the structure displacement and weight, and these were presented numerically in a spreadsheet and visually in the design tool. The results revealed there is no single best solution but a set of solutions with the best trade-offs between architectural and structural requirements. In the end, this case study proved the suitability of the ADS to assist the designer with both the creative and design analysis processes.

For future work, we plan to improve the way results are presented to the architect, which includes (1) displaying the deflected structure using a color scale, (2) showing the maximum and minimum Von Mises stresses to inform the architect whether or not the structure surpasses the maximum allowable value, and (3) providing a recommender system to guide the designer with the selection of the parameters to change in order to improve the solution's performance. Also, we plan to extend the ADS with more types of structural analysis, e.g., seismic evaluation, as well as to include other kinds of structures and shapes.

Acknowledgements

This work was supported by national funds through FCT, *Fundação para a Ciência e a Tecnologia*, under project UIDB/50021/2020 and PTDC/ART-DAQ/31061/2017, and by the PhD grant under contract of FCT with reference SFRH/BD/128628/2017.

References

Aguiar, R.: 2018, *Integrating Structural Performance in Algorithmic Design*, Master's Thesis, Instituto Superior Técnico, University of Lisbon.

Aguiar, R., Cardoso, C. and Leitão, A.: 2017, Algorithmic Design and Analysis Fusing Disciplines, *Disciplines & Disruption: Proceedings of the 37th ACADIA Conference*, MIT, Cambridge, Massachusetts, USA, 28-37.

Anton, I. and Tănase, D.: 2016, Informed Geometries. Parametric Modelling and Energy Analysis in Early Stages of Design, *Energy Procedia*, **85**, 9-16.

Belém, C. and Leitão, A.: 2019, Conflicting Goals in Architecture: A Study on Multi-Objective Optimisation, *Intelligent & Informed: Proceedings of the 24th CAADRIA Conference*, Victoria University of Wellington, New Zealand, 453-462.

Herr, C.M., Lombardi, D. and Galobardes, I.: 2018, Parametric Design of Sculptural Fibre Reinforced Concrete Facade Components, *Learning, Adapting and Prototyping: Proceedings of the 23rd CAADRIA Conference*, Tsinghua University, Beijing, China, 319-328.

Kolarevic, B.: 2003, Computing the Performative in Architecture, *Digital Design: 21th eCAADe Conference Proceedings*, 457-464.

Lee, J., Fivet, C. and Mueller, C. 2015, Modelling with Forces: Grammar-Based Graphic Statics for Diverse Architectural Structures, *in* M.R. Thomsen, M. Tamke, C. Gengnagel, B. Faircloth and F. Scheurer (eds.), *Modelling Behaviour*, Springer, Cham, Heidelberg, New York, Dordrecht, London, 491-504.

Leitão, A., Castelo-Branco, R. and Cardoso, C.: 2017, Algorithmic-Based Analysis: Design and Analysis in a Multi Back-End Generative Tool, *Protocols, Flows and Glitches: Proceedings of the 22nd CAADRIA Conference*, Suzhou, China, 137-147.

Leitão, A. and Santos, L.: 2011, Programming Languages for Generative Design: Visual or Textual?, *Respecting Fragile Places: Proceedings of the 29th eCAADe Conference*, University of Ljubljana, Slovenia, 549-557.

Leitão, A., Sousa, S. and Loio, F.: 2018, SafePath: An Agent-Based Framework to Simulate Crowd Behaviors, *Computing for a Better Tomorrow: Proceedings of the 36th eCAADe Conference*, Lodz, Poland, 621-628.

Martinho, H., Belém, C., Leitão, A., Loonen, R. and Gomes, M.G.: 2019, Algorithmic Design and Performance Analysis of Adaptive Façades, *Intelligent & Informed: Proceedings of the 24th CAADRIA Conference*, Victoria University of Wellington, New Zealand, 685-694.

Mitchell, W.J.: 1998, Articulate Design of Free-Form Structures, *Artificial Intelligence in Structural Engineering*, **1454**, 223-234.

Moon, H.J., Choi, M.S., Kim, S.K. and Ryu, S.H.: 2011, Case studies for the evaluation of interoperability between a BIM based architectural model and building performance analysis programs, *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, 1521-1526.

Mueller, C.: 2014, *Computational Exploration of the Structural Design Space*, Ph.D. Thesis, Massachusetts Institute of Technology.

Schultz, J. and Katz, N.: 2018, Origami-Inspired Facade Design: Parametric Studies for Architectural and Structural Efficiency, *Facade Tectonics 2018 World Congress*, Los Angeles, CA.

Sidelko, J.: 2013, *Museo Soumaya: Facade Design to Fabrication*, Lulu.com.

Terzidis, K.: 2006, *Algorithmic Architecture*, Architectural Press, Oxford, UK; Burlington, USA.

Turrin, M., von Buelow, P. and Stouffs, R.: 2011, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, *Advanced Engineering Informatics*, **25**, 656-675.