Graphical methods as the key to holistic design: bringing together structural design and solar control strategies

Conference Paper

Author(s):
Bertagna, Federico; Schwartz, Joseph; D'Acunto, Pierluigi

Publication date:
2022-09

Permanent link:
https://doi.org/10.3929/ethz-b-000594609

Originally published in:
Proceedings of IASS Annual Symposia 2022

Proceedings of the IASS 2022 Symposium affiliated with APCS 2022 conference
Innovation·Sustainability·Legacy
19 – 22 September 2022, Beijing, China

Graphical methods as the key to holistic design: bringing together structural design and solar control strategies

Federico BERTAGNA*, Joseph SCHWARTZ[a], Pierluigi D'ACUNTO[b]

* ETH Zurich, Dept. of Architecture, Chair of Structural Design
Stefano-Franscini-Platz 1, 8093, Zurich (Switzerland)
bertagna@arch.ethz.ch

[a] ETH Zurich, Dept. of Architecture, Chair of Structural Design
[b] Technical University of Munich, School of Engineering and Design, Professorship of Structural Design

Abstract

Building design is a complex, open-ended task that involves diverse disciplines and professionals. Architects and engineers are challenged with solving a variety of often-conflicting issues related to various aspects, such as space making, structural performance, energy consumption, and user comfort. Holistic design approaches allow for addressing all these requirements jointly from the conceptual design stage. However, it is necessary to use appropriate tools to enable effective relationships between different disciplines. The objective of this research is to introduce a new holistic framework in which structural design and solar control strategies are addressed simultaneously thanks to the use of geometry-based graphical methods. Within the framework, graphic statics serves in solving structural design aspects, while graphical methods for solar control are used to tackle solar design aspects. The results obtained show how geometry-based graphical methods lead to a concise and intuitive formulation of the problem without curtailing the precision of the results. On the contrary, the use of such methods represents a crucial advantage for designers as it fosters a thorough understanding of the underlying design principles, thus enhancing the ability of the designer of controlling the design process as a whole.

Keywords: graphical methods, structural design, solar design, graphic statics, holistic design

1. Introduction

The design of a building is a complex process of negotiation between ill-defined objectives [1] and requirements related to diverse disciplines such as architecture, structural engineering, and building physics. An effective coordination of such a complex network significantly helps in minimizing the amount of necessary material and energy resources without diminishing the quality of the outcome. *Holistic design approaches* aim at the establishment of effective relationships between the elements of this process [2], in the attempt to use available resources in the most conscious and efficient way. However, the success of holistic design approaches largely depends on the implementation of suitable frameworks and appropriate design tools.

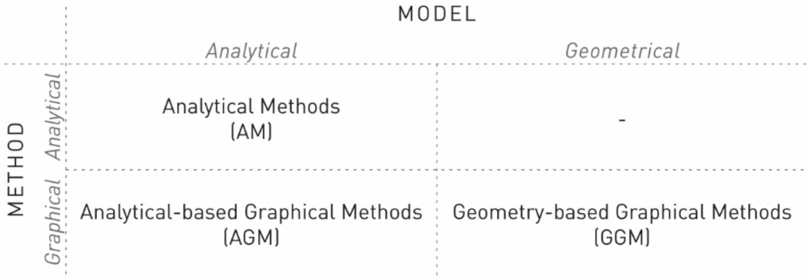
From the 1970s onwards, the development of *finite element* (FE) software [3] has introduced a new set of tools now widely used in structural engineering practice. These programs are grounded on numerical methods that – despite being powerful in solving specific tasks – offer limited support in the conceptual design stage, when the problem is not univocally defined. Building performance simulation (BPS) software for energy simulation [4] share the same limitation, being based on similarly sophisticated numerical methods. Additionally, both in FE and in BPS software, most of the necessary inputs might be unavailable in the early stages of design process. As a result, when used for design purposes these tools instigate a trial-and-error approach that does not guarantee adequate support to the designer in making informed design choices [5]. Moreover, the need for specific models also brings a further limitation when dealing with multi-disciplinary frameworks. In fact, the combination of different FE and BPS software [6], [7] requires a different model for each discipline, and the integration can only occur when evaluating the outputs of the different programs. This evaluation process is often automated through the implementation of Multi-Objective Optimization (MOO) techniques [8].

Geometry-based graphical methods offer a possible alternative to solve the limitations discussed above. These methods are grounded on purely geometrical models and exploit graphical techniques for the solution of a given problem. The geometrical nature of the methods offers the possibility of working with a single model even when dealing with multi-disciplinary design tasks. Additionally, the graphical nature helps in unfolding the relationship between inputs and outputs in a concise and intuitive way. As such, the designer can make informed design decisions in which design creativity and performance requirements coexist and reciprocally support each other.

The objective of this research is to introduce a new holistic design framework in which structural aspects and solar control strategies are considered simultaneously from the conceptual stages of the design. The framework is grounded on the use of geometry-based graphical methods as the main methodology to achieve an effective interdisciplinary approach. Despite the inherent simplicity of these methods, the results show that they lead to meaningful results and they provide a level of control to the designer that analytical-numerical methods cannot guarantee.

3. Graphical methods

In engineering related fields, the term graphical methods denotes a class of methods in which the graphical aspect is used operatively to solve a given problem. These methods can be grounded on an *analytical* model or on a *geometrical* one (Figure 1). *Analytical-based graphical methods* require an intermediary mathematical formulation of the problem, which is then resolved graphically. Conversely, *geometry-based graphical methods* do not require such intermediate step as both the formulation and the resolution process stay within the domain of geometry.



		MODEL	
		Analytical	*Geometrical*
METHOD	*Analytical*	Analytical Methods (AM)	-
	Graphical	Analytical-based Graphical Methods (AGM)	Geometry-based Graphical Methods (GGM)

Figure 1: Possible combinations model-method. Unlike graphical methods that can be grounded on both analytical and geometrical models, analytical methods are compatible with analytical models only.

3.1 Analytical-based Graphical Methods (AGM)

Analytical-based graphical methods significantly facilitate calculation processes, proving particularly effective when limited computational capacity is available. *Nomograms* (or *alignment charts*) belong to this first class of graphical methods. They provide a planar representation of mathematical laws in a graphical way [9], simplifying the resolution process to the point that the knowledge of the underlying equations is not necessary anymore to solve the problem.

3.2 Geometry-based Graphical Methods (GGM)

In structural engineering, graphic statics [10] is one of the most prominent examples of geometry-based graphical methods. Through a set of geometric rules and constructions, it describes graphically the relationship between the form of a load-bearing structure and the forces within it under a given load case. The method comprises two reciprocal diagrams: the *form diagram* depicts the shape of the load bearing structure, while the *force diagram* depicts the forces within it. Metric and/or topological transformations of one of the two diagrams results in a consequent transformations of the other diagram, and vice versa. During the 20th century, the introduction of the theory of plasticity determined a renewed interest towards graphic statics. In particular, the lower bound theorem of the theory of plasticity provided a solid theoretical basis to equilibrium-based design [11]. Graphic statics provides a convenient way to describe this, illustrating the relationship between form and forces in a concise and explicit way [12]. Moreover, recent digital implementations significantly helped in overcoming the limitations connected to a manual application of the method. This resulted in the development of computational tools and applications that greatly enhance the potential of the method [13]–[15].

Similar to the case of graphic statics in structural engineering, graphical methods were developed also in the field of solar control for buildings. The pioneering work of the architect Victor Olgyay (1910-1970) in the field of bioclimatic design is an exemplary case. The objective of his work was to provide practicing architects with simple design tools and frameworks that would support them in the design of energy efficient and comfortable buildings [16]. Olgyay's method for solar control aims at unfolding the relationship between the shape of a shading device and its performance and comprises two diagrams: the *overheated period diagram* and the *shading mask*. The overheated period diagram shows the position of the sun when the external air temperature exceeds a certain comfort threshold. This gives information on when it is necessary to provide shading. The shading mask represents the shading performance of a shading device with respect to a given point. The two diagrams can be then superimposed in order to evaluate the performance of a given shading device (*analysis problem*), or to design shading devices in order to achieve a given performance (*design problem*).

Based on a similar approach, Piotr Kowalski (1927-2004), one of Olgyay's students, developed another graphical method based on geometrical projections and line-to-line intersections. The Breuer-Kowalski method [17] shows the percentage of solar radiation that a shading device is able to block before it reaches a given surface, representing the results in the form of hourly irradiation curves.

Unlike graphic statics, graphical methods for solar control are still considered outdated. The use of more sophisticated numerical-based simulation tools is favored, even though they cannot guarantee the same concise and diagrammatic character of geometry-based graphical methods [5]. The revival of graphic statics has demonstrated that geometry-based graphical methods can still be regarded as valid design and analysis tools, especially when combined with the computational power available nowadays.

3.3 The two-fold advantage of geometry-based graphical methods for design

In the context of holistic design, the use of geometry-based graphical methods brings a twofold advantage. First, a geometric formulation of the problem leads to a single model through which aspects belonging to diverse disciplines can be addressed simultaneously. This eliminates the need for multiple models, as it is often necessary in multi-disciplinary frameworks [6], [7]. In this research, this is demonstrated by integrating structural design and solar control as part of the same design framework. A second advantage of geometry-based graphical methods lays in the fact that relationships between design parameters and between inputs and outputs become explicit. This fosters an intuitive understanding of the underlying design principles, thus supporting the designer in making informed decisions from the conceptual stages of the design.

4. Design framework

Figure 2 illustrates the proposed design framework in the form of a flowchart. Starting from the given *design inputs* – which also include the architectural concept – a set of *design criteria* and a *geometrical model* are defined. This model describes all the different aspects and disciplines jointly and becomes the basis for different graphical methods to operate. *Geometry-based design explorations* are performed as part of a first feedback loop. The solutions of these explorations that fulfil the given metrics are transferred to a *pool of possible solutions*, which constitutes the output of the conceptual design stage.

It is worth mentioning that the use of geometry-based graphical methods greatly reduces the amount of time invested on refined analyses of solutions that eventually are not meaningful with respect to the design objectives. This does not suggest that advanced analyses that go beyond the geometrical formulation are not necessary. The framework rather intends to highlight that their implementation should occur in a more advanced stage of the design, and only on a limited number of solutions that comply with basic, yet crucial design criteria that are addressed in the conceptual stage of the design.

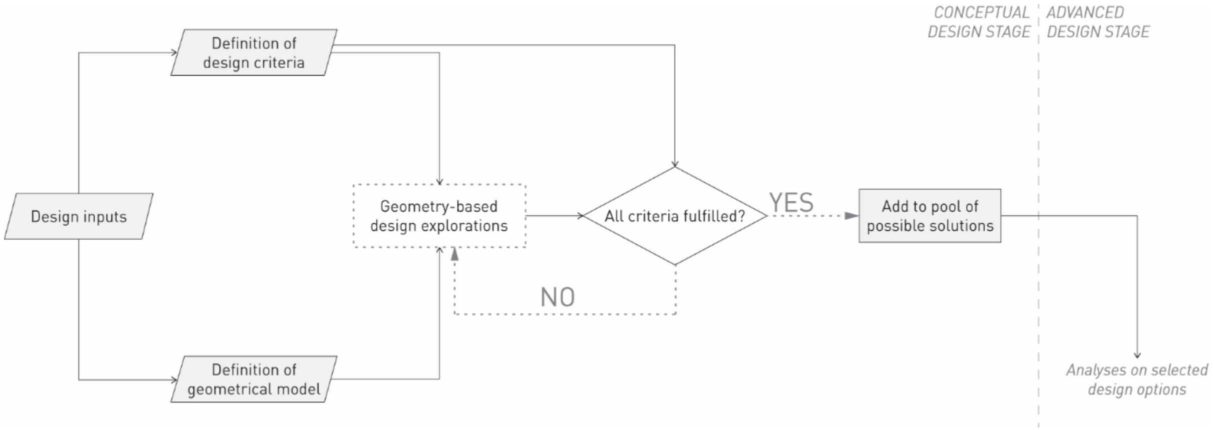


Figure 2: In the proposed design framework, starting from given design inputs, the designer defines a set of design criteria and a geometry-based model suitable for the task. Based on these design criteria and using the geometry-based model, the designer can now explore the design space with the support of graphical methods. All the design options that fulfil the design criteria can be added to a pool of possible solutions. As such, refined analyses can be performed only on a limited set of solutions that already comply with basic, yet crucial design criteria.

The proposed design framework is further illustrated through an application involving long-span frame buildings. Other than being the main load-bearing element, the frame also protects the south-facing glazed surfaces in between the bays from direct solar radiation. The climate data used in this case study refer to the city of Barcelona (Köppen-Geiger maritime Mediterranean climate). The structural performance is evaluated considering a load case that comprises a distributed vertical load of 100 kN/m. It is worth mentioning that both the climate data and the load case were introduced with the sole intent of making the comparison between diverse options possible.

In Figure 3, the form and force diagrams clearly show how the form of the structure affects the forces that develop within it, depicting the nature of these forces (i.e. tension or compression), their distribution within the material, and their intensity. This also helps the designer to detect the zones with highest internal forces at a very early stage and to compare the global structural behavior of diverse design options.

In addition to the structural function, the frame is also intended to provide solar protection to the South-facing glazed surfaces along the building. The combination of shading mask and sun-path diagram depicts the period during which the structure blocks direct solar radiation, referring to the mid-point at the bottom of the South-facing glazed surface, which is marked in magenta. The superposition of the overheated period diagram shows whether such solar protection is beneficial or not. Finally, the irradiation charts show shading performance of the different geometries with respect to two design days (June 21st, December 21st) that exemplifies summer and winter climate conditions. These diagrams refer to the South-facing glazed surface marked in light blue.

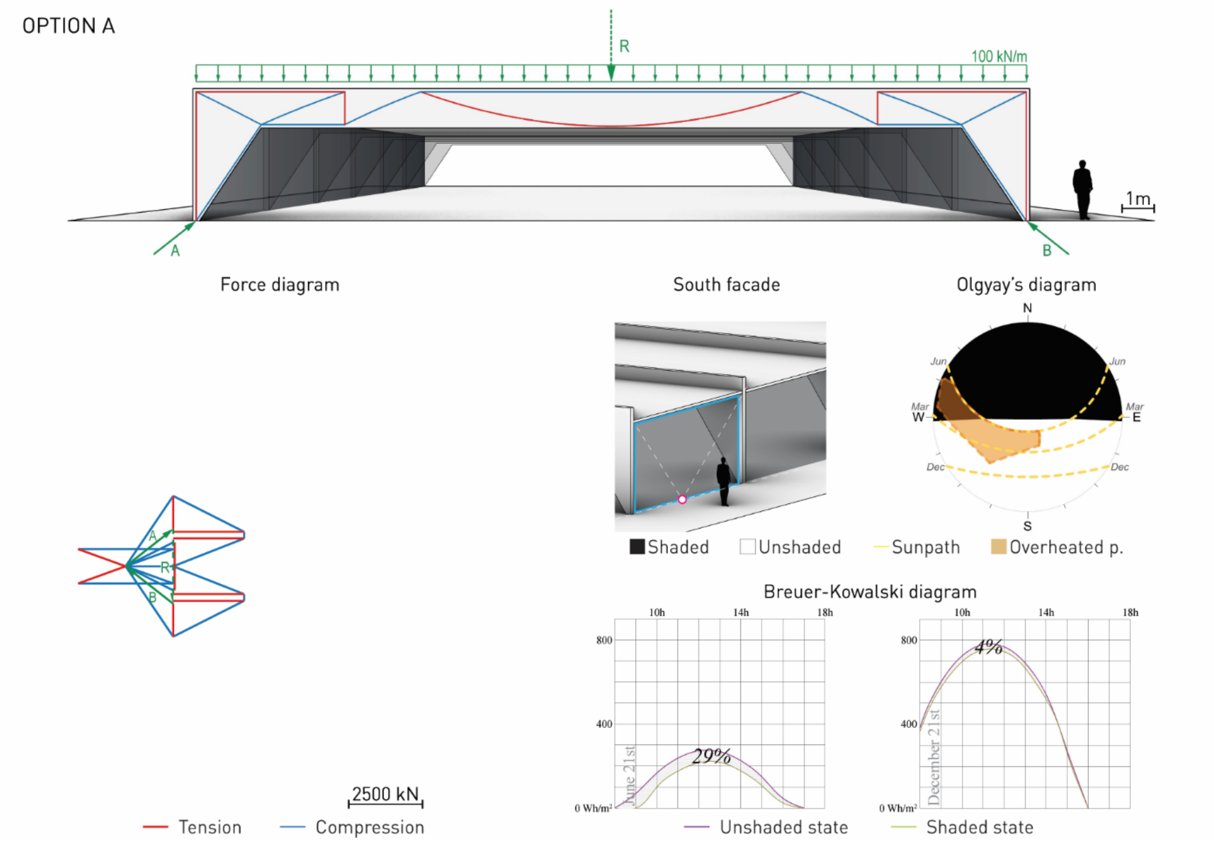
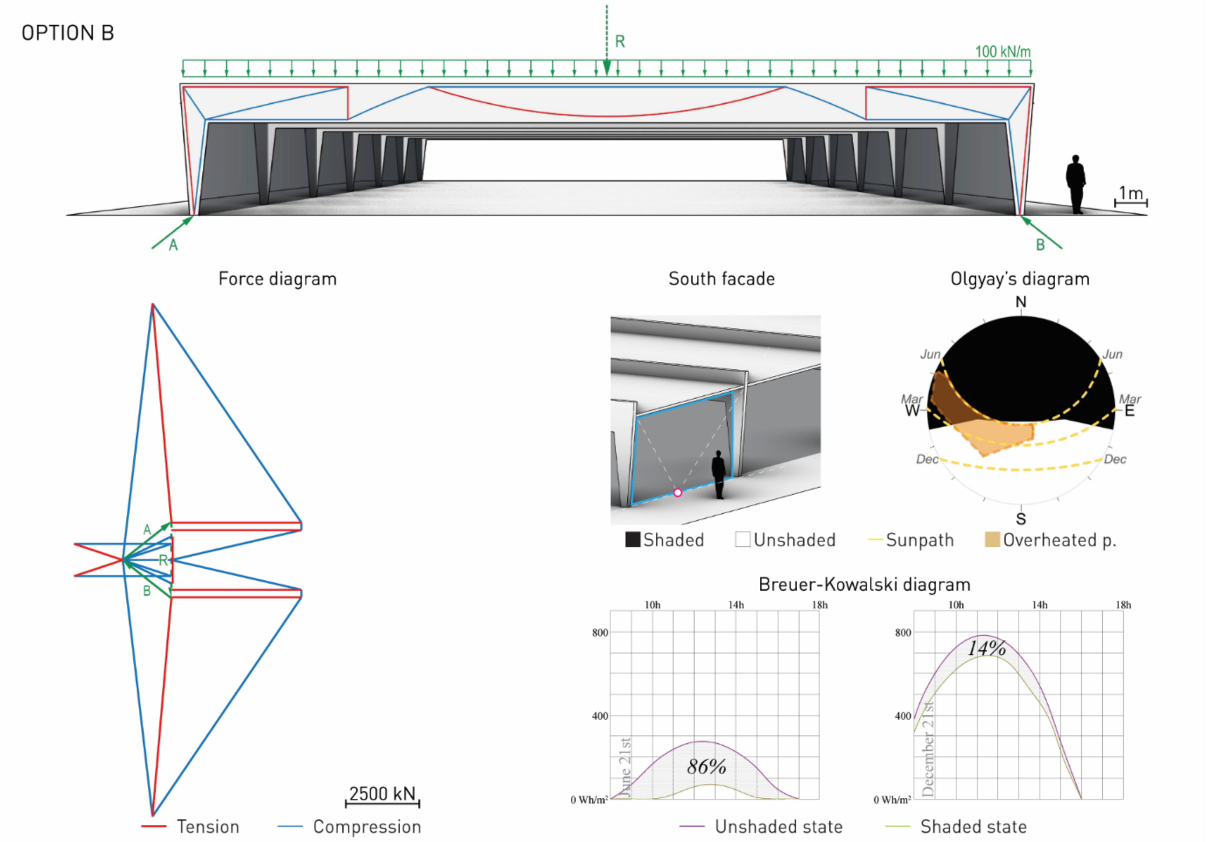
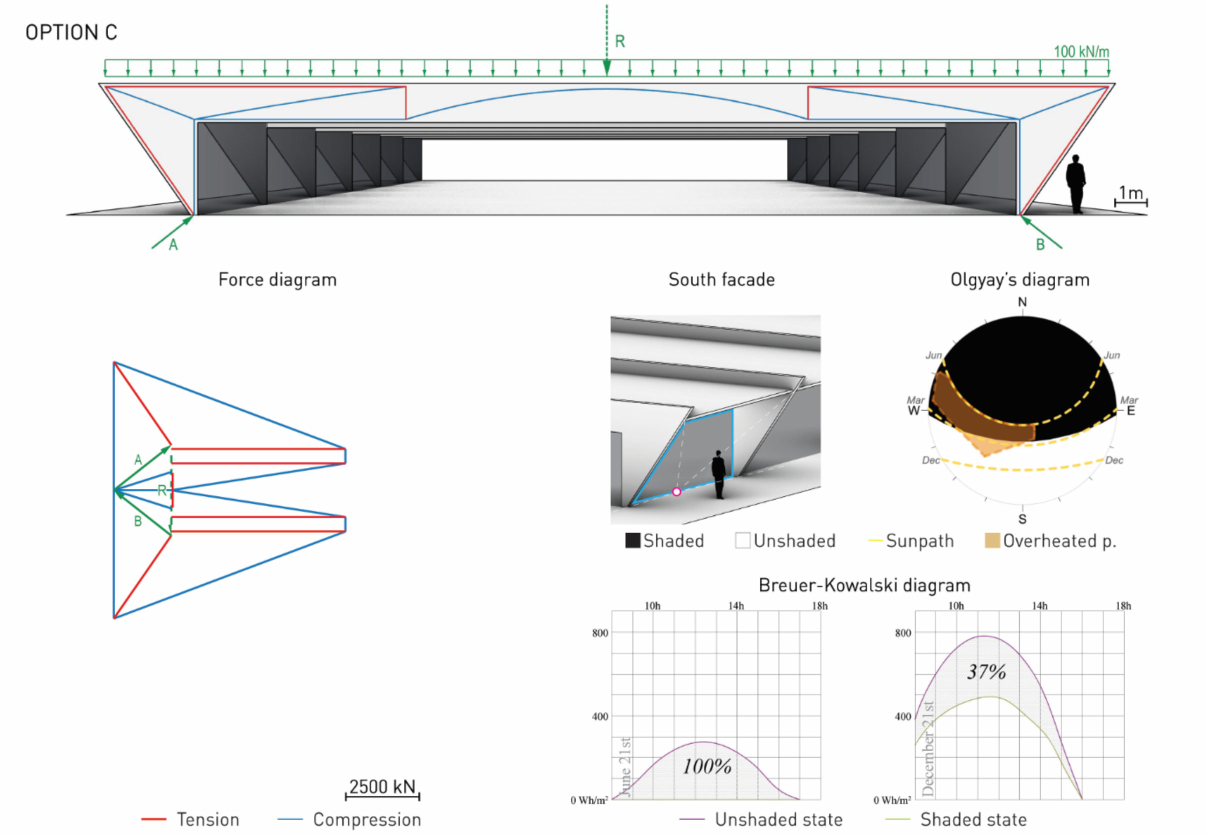


Figure 3: (above and next page) An application of the proposed framework: the use of geometry-based graphical methods as a tool to unfold the relationship between form, forces, and shading performance. In particular, graphic statics unfolds the relationship between form and forces, while Olgyay's method and Breuer-Kowalski method unfold the relationship between form and shading performance.


OPTION B
R
100 kN/m
A
B
1m
Force diagram
A
R
B
2500 kN
Tension
Compression
South facade
Olgyay's diagram
N
Jun
Jun
Mar
W
Mar
E
Dec
Dec
S
Shaded
Unshaded
Sunpath
Overheated p.
Breuer-Kowalski diagram
10h
14h
18h
800
400
0 Wh/m²
June 21st
86%
10h
14h
18h
800
400
0 Wh/m²
December 21st
14%
Unshaded state
Shaded state


OPTION C
R
100 kN/m
A
B
1m
Force diagram
A
R
B
2500 kN
Tension
Compression
South facade
Olgyay's diagram
N
Jun
Jun
Mar
W
Mar
E
Dec
Dec
S
Shaded
Unshaded
Sunpath
Overheated p.
Breuer-Kowalski diagram
10h
14h
18h
800
400
0 Wh/m²
June 21st
100%
10h
14h
18h
800
400
0 Wh/m²
December 21st
37%
Unshaded state
Shaded state

As shown by the force diagram, Option A is characterized by relatively small inner forces that follow a typical frame-like distribution. However, the shading performance is rather poor throughout the entire year. The shading mask shows that the frame is able to provide some shading to the glazed surface only between March and September, and only during early morning hours and late afternoon. As such, the mask does not cover the vast majority of the overheated period diagram, thus significantly increasing the risk for indoor overheating and increased cooling energy demand.

In the attempt to improve the shading performance, Option B shows a design variation with a different shape for the frame. This results in better shading performance during summer mainly because the increased depth of the roof overhang. However, the proposed shape shows a significantly worse structural performance, with very high forces around the corner of the frame and along the columns.

Option C results in the best shading performance by far, with a structural performance that can be regarded as compromise between Option A and Option B.

Eventually, the choice for the most suitable options strongly depends on the problem at hand, assuming that different design aspects might have different relevance depending on the context. As Figure 3 shows, the diagrammatic nature of geometry-based graphical methods ultimately allows for a systematic comparison of diverse options, thus giving the designer all the necessary elements to make informed design decisions.

5. Discussion and conclusions

This paper presented a holistic framework for the conceptual design of load-bearing and sun-shading building elements. The use of geometry-based graphical methods was the key to achieve a seamless integration of diverse disciplines within the same design framework. The results showed that despite the inherent simplicity of geometry-based graphical methods, it is possible to retrieve meaningful results that significantly help the designer in the conceptual stage of the design. In fact, the inherent simplicity and diagrammatic nature of the methods allow for an enhanced control and intuitive understanding of the relationships between design parameters without necessarily resorting to trial-and-error routines. Moreover, the present paper also shows how digital implementations can support and enhance the potential of existing manual design methods. This was already shown in the field of graphic statics in the last decades by several authors [13], [14], but not yet in the field of solar control.

A limitation of the proposed framework is that, by using a geometry-based approach, only those aspects that bear a geometrical formulation can be included. The question becomes whether aspects that cannot be described through geometry play a primary role in the conceptual design stage or they can be included at a later stage in the process instead. Further design applications will be necessary to understand the actual extent of this limitation. Future work will also focus on different geometry-based graphical methods as well as on alternative ways to combine the ones presented here in different frameworks specifically tailored for given design problems.

References

[1] B. Lawson, *How Designers Think*. Architectural Press, 2005.

[2] M. Zanuso, "Il progetto nel processo edilizio," *Spazio e società, n.3*, pp. 95–100, 1978.

[3] O. C. Zienkiewicz, R. L. Taylor, and J. Z. Zhu, *The Finite Element Method : Its Basis and Fundamentals*. Elsevier Ltd, 2013.

[4] J. Hensen and R. Lamberts, "Introduction to Building Performance Simulation," in *Building Performance Simulation for Design and Operation*, 2011.

[5] T. Kotnik and P. D'Acunto, "Operative Diagramatology: Structural Folding for Architectural Design," in *Rethinking Prototyping: Proceedings of Design Modelling Symposium Berlin 2013*, 2013, pp. 193–203.

[6] D. Yang, S. Ren, M. Turrin, S. Sariyildiz, and Y. Sun, "Multi-disciplinary and multi-objective optimization problem re-formulation in computational design exploration: A case of conceptual sports building design," *Autom. Constr.*, vol. 92, pp. 242–269, Aug. 2018, doi: 10.1016/J.AUTCON.2018.03.023.

[7] N. Brown and C. Mueller, "Design for structural and energy performance of long span buildings using geometric multi-objective optimization," *Energy Build.*, vol. 127, pp. 748–761, 2016, doi: 10.1016/j.enbuild.2016.05.090.

[8] R. T. Marler and J. S. Arora, "Survey of multi-objective optimization methods for engineering," *Struct. Multidiscip. Optim.*, vol. 26, no. 6, pp. 369–395, 2004, doi: 10.1007/s00158-003-0368-6.

[9] A. S. Levens, *Graphical Methods in Research*. New York, London, Sydney: John Wiley & Sons, 1965.

[10] C. Culmann, *Die Graphische Statik*. Zurich: Meyer & Zeller, 1866.

[11] J. Schwartz, "Bending and confusion," in *Before Steel*, M. Rinke and J. Schwartz, Eds. Zurich: Verlag Niggli AG, 2010, pp. 193–209.

[12] E. Allen and W. Zalewski, *Form and Forces*. John Wiley & Sons, 2009.

[13] T. Van Mele, L. Lachauer, M. Rippmann, and P. Block, "Geometry-based understanding of structures," *J. Int. Assoc. Shell Spat. Struct.*, vol. 53, no. 174, pp. 285–295, 2012.

[14] P. O. Ohlbrock and P. D'Acunto, "A Computer-Aided Approach to Equilibrium Design Based on Graphic Statics and Combinatorial Variations," *CAD Comput. Aided Des.*, vol. 121, 2020, doi: 10.1016/j.cad.2019.102802.

[15] P. D'Acunto, J. P. Jasienski, P. O. Ohlbrock, C. Fivet, J. Schwartz, and D. Zastavni, "Vector-based 3D graphic statics: A framework for the design of spatial structures based on the relation between form and forces," *Int. J. Solids Struct.*, vol. 167, pp. 58–70, 2019, doi: 10.1016/j.ijsolstr.2019.02.008.

[16] V. Olgyay, *Design with climate : bioclimatic approach to architectural regionalism*. New Jersey: Princeton University Press, 1963.

[17] S. Howard, "How Solar and Temperature Studies Guided Design of Sunshades for UNESCO Headquarters," *Architectural Record*, pp. 226–229, 1959.