Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Unlocking Architectural Potential: The Synergy of One Single Model and Meta-Designer in Parametric Innovation

Federico Mario La Russa*, Antonio Diaferia

*Maffeis Engineering
Via Mignano 26, Solagna (VI), Italy
f.larussa@maffeis.it

Abstract

Parametric modeling stands out as a powerful tool in modern design methodologies, up to transitioning the focus from 'how to model' to 'how to build.' This pivotal shift underscores the essence of Maffeis Engineering’s One Single Model approach, that seamlessly facilitates effective, elegant, and sustainable solutions among diverse AEC professionals. Amidst the complexity of architectural designs, swift resolutions to challenges such as clashes, fabricability issues, and logistical complexities demand a paradigm shift. This shift urges experts from varied domains to converge in a shared digital space characterized by high interoperability, responsiveness, and flexibility. In this innovative landscape, the role of AI is increasingly prominent empowering designers with speed and imagination, especially in shell and spatial structures. AI's advancement in design intensifies the urgency of keeping up with the pace. This transformation fosters collaboration among diverse teams navigating challenges collectively. Through parametric design, professionals shift towards a unified 'meta-designer' approach redefining computational design as a shared space beyond individual specialties. This paper will present how Maffeis Engineering's OSM approach effectively tackles these challenges showing compelling case studies.

Keywords: One Single Model, form finding, optimization, computational design, free-form, ETFE, shell, spatial structures, membrane structures, AI

1. Introduction

1.1. Nowadays parametric design processes in the domain of free form and tensile structures

Parametric modeling and computational design have revolutionized the architectural landscape offering dynamic methodologies that transcend traditional approaches and unlock new possibilities in design, analysis, and fabrication. In this context, tensile structures, including membrane and cable structures, have emerged as prominent components within civil engineering and architecture boasting a diverse range of applications from iconic landmarks to small-scale canopies. These structures typically utilize materials such as polyvinyl chloride (PVC) or polytetrafluoroethylene (PTFE) coated fabrics reinforced with steel cables renowned for their flexibility and resistance to bending moments. However, this flexibility also renders them susceptible to large displacements and wrinkles under compressive forces necessitating advanced nonlinear static analysis techniques for accurate stress and displacement evaluation. The design process for tensile structures is multifacete, often comprising four main steps:

form-finding, geometrically nonlinear structural analysis, patterning, and flattening of fabric strips. Form-finding seeks to establish an equilibrium shape under predetermined initial stress and boundary conditions ensuring architectural requirements are met. Structural analysis then evaluates the system's response to external loads balancing safety and functional criteria. Fabrication of tensile structure fabrics presents unique challenges, particularly in transitioning from 3D shapes to 2D geometries. Patterning subdivides the 3D surface into fabric strips to accommodate manufacturing restrictions and minimize deviation from the idealized geometry. The flattening process refines each strip into a 2D shape considering prestress compensation to achieve the desired shape upon assembly. The introduction of materials such as ethylene tetrafluoroethylene (ETFE) has further expanded the realm of tensile structures offering enhanced transparency, durability, and environmental sustainability. ETFE's unique properties enable the creation of lightweight, flexible, and energy-efficient architectural solutions pushing the boundaries of architectural expression (de Souza et al. [1]).

In this dynamic context, parametric modeling and computational design play pivotal roles offering designers unprecedented tools to explore, iterate, and realize complex geometries and innovative structural solutions. By harnessing the power of computation, architects and engineers can navigate the complexities of tensile structure design with precision and efficiency creating structures that not only inspire but also respond harmoniously to their environment (Füzes et al. [2]). Through interdisciplinary collaboration and innovative methodologies, architects and engineers can continue to push the boundaries of architectural innovation creating sustainable and visually compelling built environments for future generations.

1.2. Challenges and impact of AI implementation in AEC practices

The integration of artificial intelligence (AI) in architectural design processes has ushered in a revolutionary era empowering architects and clients to explore an unprecedented array of design possibilities with unparalleled speed and efficiency. AI algorithms equipped with generative design capabilities enable architects to envision and evaluate countless iterations of a design allowing for the rapid exploration of diverse architectural forms and configurations. However, this paradigm shift towards AI-driven design presents significant challenges for engineering firms and other stakeholders within the architecture, engineering, and construction (AEC) sector (Maureira et al. [3]).

As architects leverage AI tools to generate and refine design concepts with unprecedented speed and complexity, engineering firms are tasked with adapting their workflows and methodologies to keep pace with this accelerated production of designs. The need to analyze and validate a vast number of design iterations within tight project timelines necessitates the development of scalable computational frameworks and efficient collaboration mechanisms. Additionally, engineering firms must grapple with the intricacies of interpreting and integrating AI-generated designs into the broader architectural and engineering context ensuring structural integrity, regulatory compliance, and constructability. The integration of AI in architectural design processes introduces new considerations regarding data interoperability, privacy, and security. Collaborative efforts highlight the importance of establishing robust data governance frameworks and ethical guidelines to safeguard sensitive project information and foster trust among stakeholders (Maksoud et al. [4]).

While AI-driven design holds immense potential to revolutionize architectural practice, its implementation poses significant challenges for engineering firms and the broader AEC sector. It's essential to recognize that AI is not autonomous, particularly in the engineering sector; it facilitates but does not replace human expertise. The ultimate goal remains the same: delivering a product that meets the needs of the client and the community. Computational design should be viewed as a means to an end, not an end in itself, emphasizing the importance of maintaining a human-centered and team-oriented approach to design and construction processes.

1.3. The need of collaborative Computational Design based workflows in the future of AEC

In this atmosphere of innovation, the vanguard of computational design will become more and more commonplace having to deal with ever more demanding architectural-engineering challenges and with increasingly constrained timeframes. Given this scenario, there is a need to review how firms in the AEC sector manage all roles as they cannot relegate computational design to a practice of a few specialists but to a common methodology involving all roles in design teams.

Computational design often remains a specialized skill set accessible only to a select group of specialists creating a distinct separation between computational designers and other roles within AEC firms. Despite the potential for computational design to revolutionize the industry by facilitating complex geometries, optimizing performance, and streamlining workflows, its adoption has been hindered by a significant skills gap and lack of widespread integration into mainstream design practice (Mikaelsson [5]).

Scholarly research and industry analyses have revealed a significant disparity within the AEC sector. It appears that computational design tools are not universally accessible or utilized among design professionals. This suggests a gap in skills and training hindering the effective leverage of these tools in practice. Furthermore, the distinction between computational designers and other roles within AEC firms exacerbates this divide. Computational designers, often equipped with specialized knowledge in programming, parametric modeling, and algorithmic design, operate as a distinct subset within the broader design team. Their expertise enables them to tackle complex design challenges and develop innovative solutions using computational tools and methodologies (Holzer [6], Indraprastha [7]).

This segregation between computational designers and traditional design roles perpetuates a cycle of dependency wherein computational design is perceived as an auxiliary service rather than an integral component of the design process. As a result, AEC firms may underutilize the potential of computational design to drive innovation and efficiency across all stages of the design and construction lifecycle.

2. One Single Model methodology and the ‘Meta-Designer’ concept

Maffeis Engineering adopts a comprehensive methodology centered around the One Single Model (OSM) approach integrating a cluster of interconnected software and tools, many of which are internally developed or linked with API (application programming interface). This methodology encompasses precise schemes and workflows, managing input data from geometric models to finite element method (FEM) analyses and Building Information Modeling (BIM) models, and vice versa. The OSM framework orchestrates technical reports, automatic verifications, IFC drawings, and BIM output, all seamlessly linked and live-linked at the programmers' level. At the core of the OSM is a visual programming interface designed to be intuitive for engineers, architects, and programmers alike with clearly defined input and output modules. This methodology requires upfront effort but yields substantial advantages as subsequent phases of the project are controlled within this canvas including FEM analysis and BIM modeling. The control panel, typically developed using software like Grasshopper and Dynamo, is adaptable to varying design processes and phases from concept to execution. Each design process, tailored to megastructures and unique buildings, receives a bespoke approach within the open architecture of the OSM ensuring flexibility and adaptability.

The OSM approach is not meant to be a linear or “one-way” iterative workflow. Instead it can be adapted dynamically, revisiting and integrating every phase as needed. Information is managed within the parametric environment, ensuring continuous updates and synchronization without relying solely on the interoperability capabilities of specific software (Sattler et al. [8]). This flexibility allows for efficient coordination and seamless information exchange throughout the design process given the grannularity of data achiveable through this parametric approach (Figure 1).

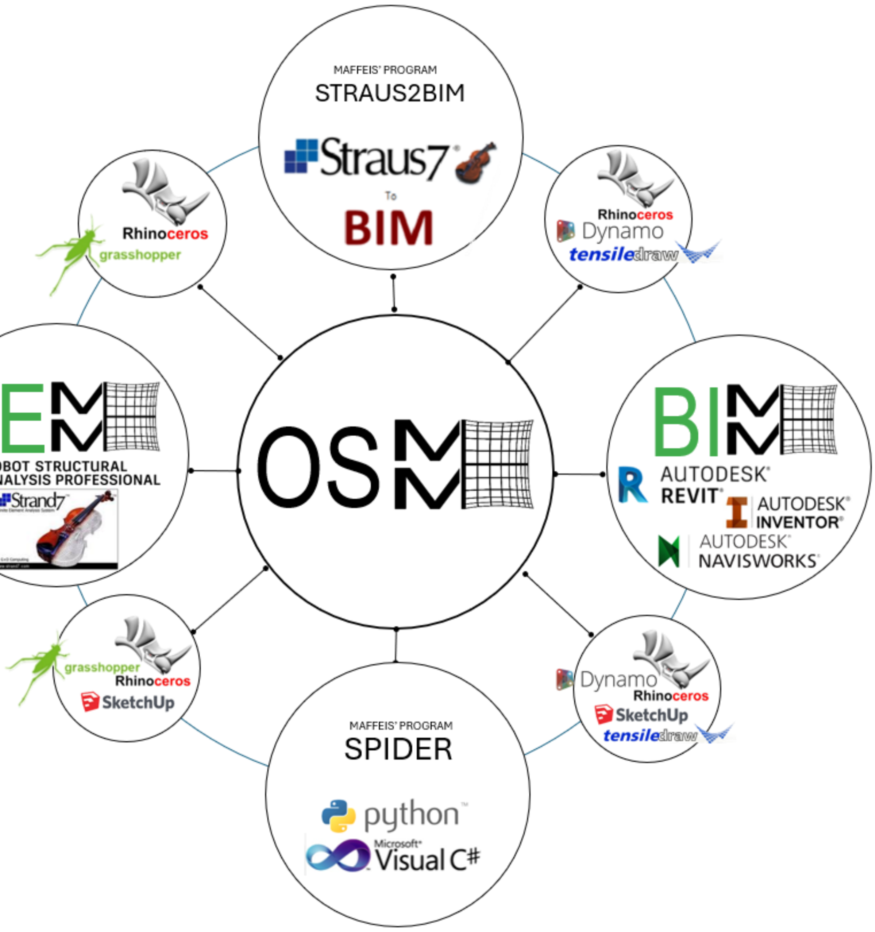

Figure 1: Conceptual diagram of the One Single Model framework. The diagram represents the overview of some of the main working environments that are adopted. Usually, the starting point is a parametric model developed with Grasshopper or Dynamo script utilized to generate, control and update both the FEM and the BIM models.

This inventive strategy not only empowers diverse experts to assess potential solutions efficiently but also transforms the design process into a collaborative arena. At the core of this collaborative approach lies a fundamental understanding of parametric design principles among all team members ensuring a common language and framework for design exploration. To facilitate the integration of new team members, Maffeis Engineering extensively employs ready-for-use Grasshopper and Dynamo templates providing a standardized starting point for designers entering the team. These templates serve as scaffolds for design exploration offering predefined modules and workflows tailored to specific project requirements. Within this framework, established communication keywords between team members based on specific parts of the templates facilitate efficient collaboration and knowledge sharing.

The OSM approach not only enhances interoperability but also facilitates informed decision-making processes. For instance, in the context of tensile structure design, hybrid FEM models comprising both membranes and primary steel elements are utilized to achieve efficient structures. During the design optimization phase conducted by structural engineers, computational designers employ rule-based modeling within the OSM to distribute pre-dimensioned secondary elements for anchoring the membranes. Then, the model goes through a cycle of checks and verifications in order confirm the design choices. This integrated model allows to not separate BIM and FEM modeling efforts. Consequently, both the geometric and analytical model configurations can be continuously updated throughout the design process, ensuring optimal performance and adaptability. This procedure is also applied every time generative design methodologies are employed for reaching target goals requested specifically from the client's requirements for aesthetic and/or functional purposes.

Furthermore, all comments, notes, and feedback from the client are discussed, shared, and modified directly within the parametric model ensuring that design decisions are informed by client preferences and requirements. This holistic approach enables each team member, regardless of their main field of expertise, to contribute to the pipeline of work and enhance the quality of the project. The collaborative nature of this process leads to teams that function as a single designer expert in many disciplines, responsive to clients' input and needs while effectively addressing engineering challenges. While specialists play a crucial role in providing in-depth expertise and guidance, they are also actively involved in the entire design process, collaborating with other team members to refine and optimize design solutions. This collaborative and inclusive approach not only enhances the efficiency and effectiveness of the design process but also fosters a culture of continuous learning and improvement within the team (Figure 2).

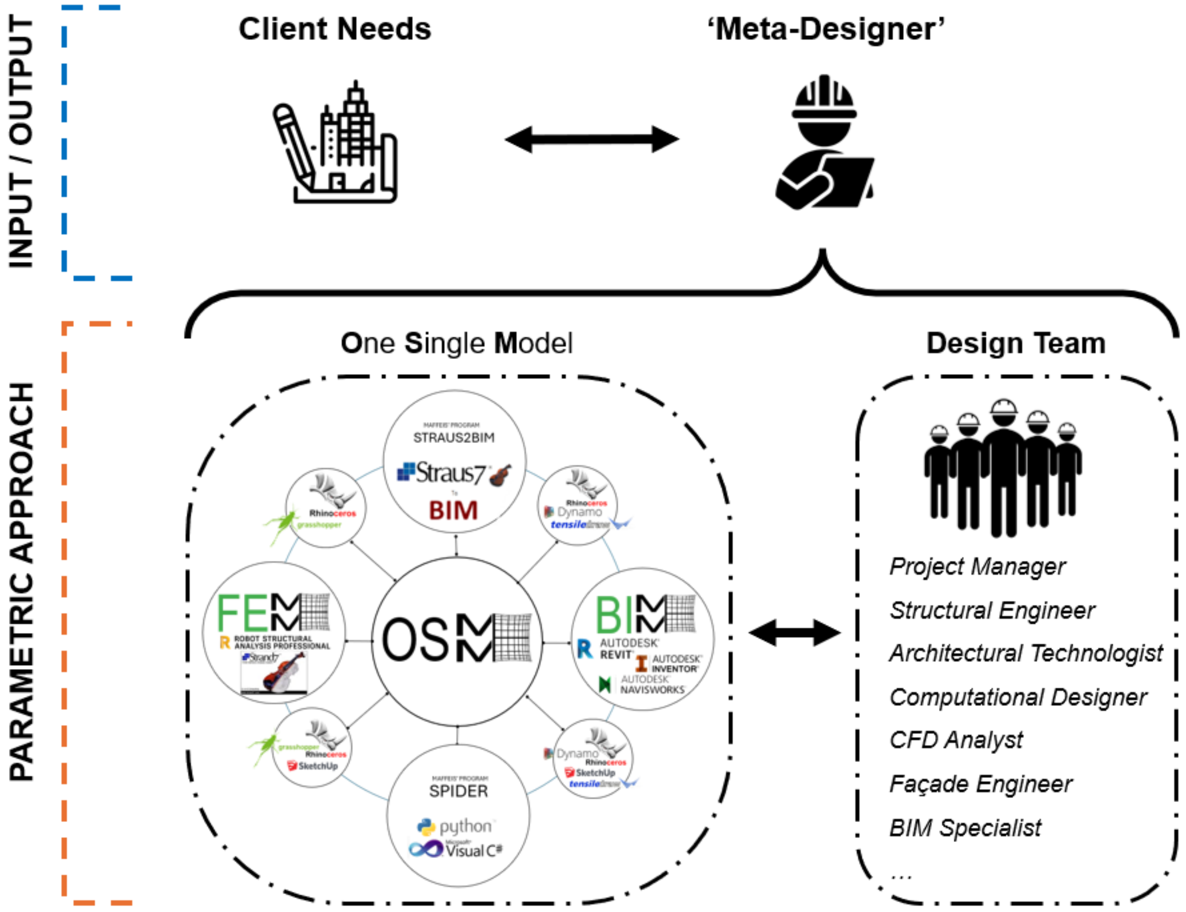

Figure 2: Meta-Designer Concept Outline. Each design team possesses knowledge and tools to be able to carry out their work within the One Single Model framework. The synergy of the OSM allows all members to follow the status of the project as a single designer (Meta-Designer) enabling a direct relationship with the client's needs. The relationship between client and meta-designer constitutes inputs and outputs of the OSM.

The collaborative approach adopted by Maffeis Engineering, exemplified through the One Single Model (OSM), has demonstrated its effectiveness in addressing architectural challenges particularly within the domain of shell and spatial structures including those integrating ETFE technology. Within the OSM's parametric framework, complex form-finding and optimization processes are navigated with enhanced efficiency and precision. This methodology facilitates iterative exploration and refinement of design solutions seamlessly integrating structural analysis and performance evaluation into the workflow. For ETFE free-form projects the OSM facilitates the generation of shop drawings and BIM models within the parametric model, streamlining processes from concept to delivery. During the whole process the parametric model has been visualized and shared with the client at each stage through the web based model explorer Cubinto. This integrated approach aims to meet project objectives with innovative and sustainable solutions without losing sight of the architectural intent during the whole process.

3. Exploring Exemplary Projects: experiences of OSM and meta-designer to free-form architectures with ETFE membranes

In this section dedicated to illustrative projects, we delve into real-world applications of parametric design and computational methods drawing from Maffeis Engineering's extensive experience, particularly in the domain of free-form structures with membranes. Each case study illuminates the practical implementation of these methodologies within the realms of architecture and civil engineering showcasing projects where Maffeis Engineering's One Single Model (OSM) plays a pivotal role. Through these examples, we highlight how the OSM fosters efficient process management and ensures the delivery of high-quality outcomes in the context of free-form structures with membranes.

3.1. Entrance Canopy of the Singapore Oceanarium

The new Entrance Canopy for the Singapore Oceanarium in the island of Sentosa is exemplificative of an optimization experience while maintaining as intact as possible the original architectural intent. The design entails 8 distinct bays each hosting a free-form surface that delineates the path of ETFE cushions. This configuration results in each cushion being unique in its form and specifications. Our task was to meticulously optimize the number of cushions while preserving the architectural vision intact (Figure 3).

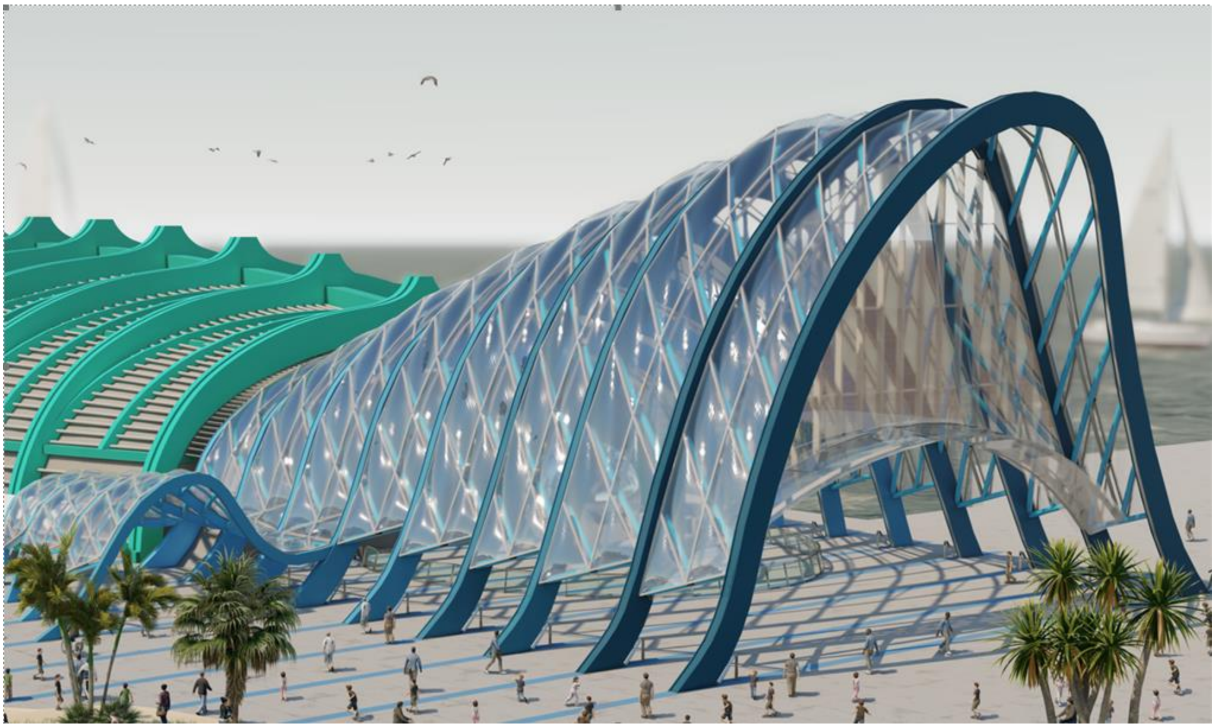

Figure 3: Render picture of the architectural tender model.

This task was pursued through a combined action of geometric study of the development of bay reference surfaces and clustering by AI (specifically Machine Learning with a K-Means algorithm) of ETFE cushions. The goal was to obtain groupings such that each ETFE cushion type had the same cutting pattern considering the design tolerance. In order to obtain better groupings, the arcs' shapes were modified while preserving the original architectural intent. The OSM framework made it possible to keep the FEM and Revit model updated, that were used internally for structure verification and production of fabrication drawings. The work team of structural engineers, architects, and computational designers constantly worked on the parametric model as a starting point for any output and verification during client meetings. The project is still ongoing with refinements on optimization solutions (Figures 4, 5, 6).

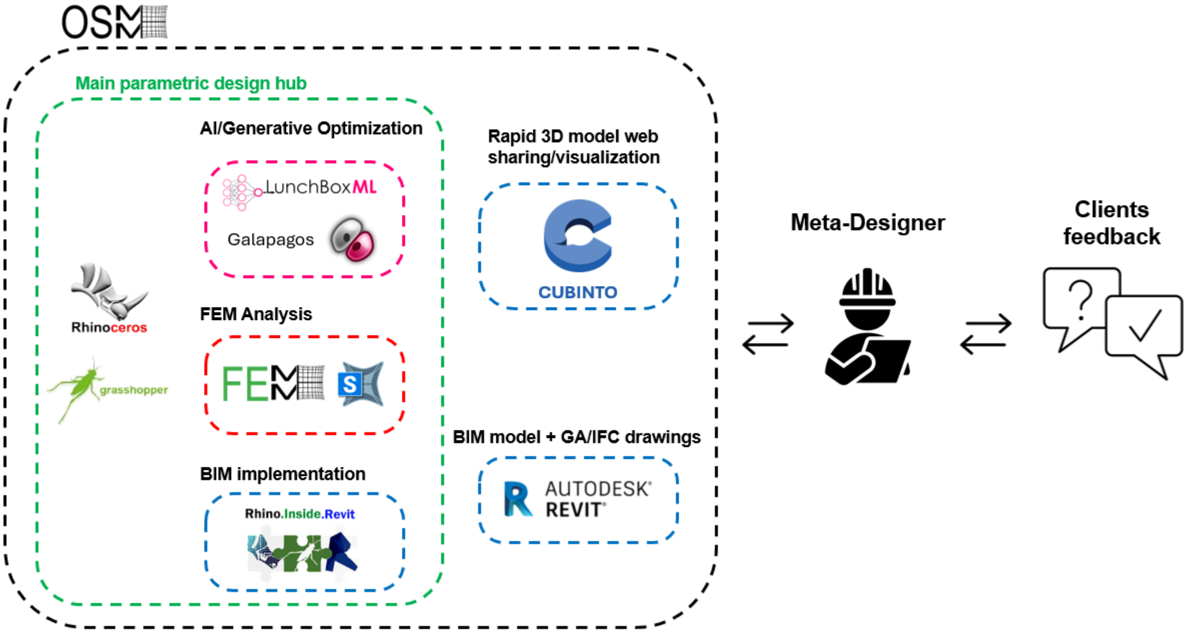

Figure 4: Concept scheme of the pipeline of work adopted.

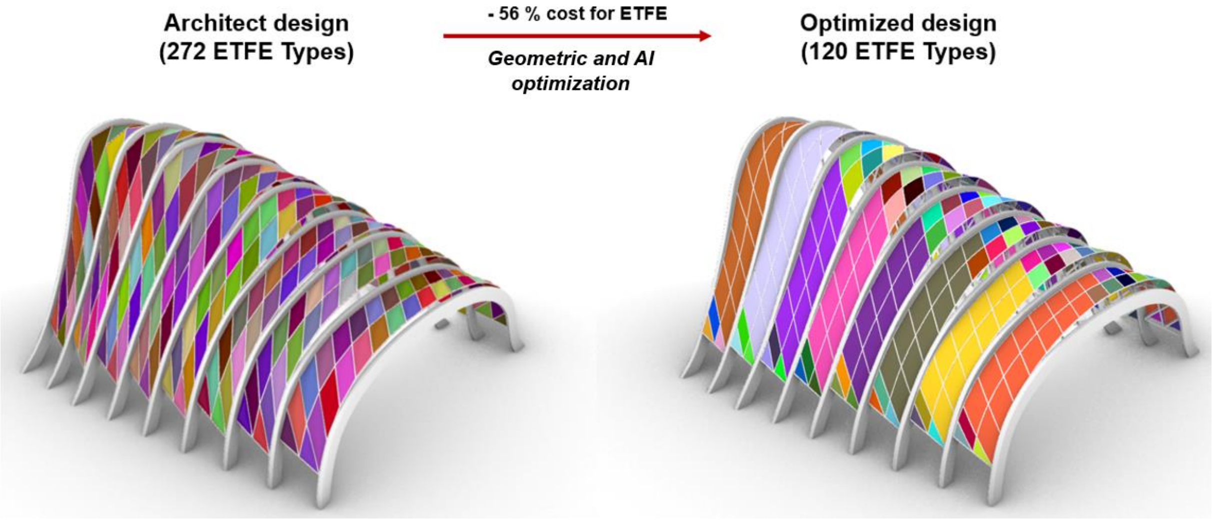

Figure 5: Early-stage results of geometric and AI ETFE cushion types optimization.

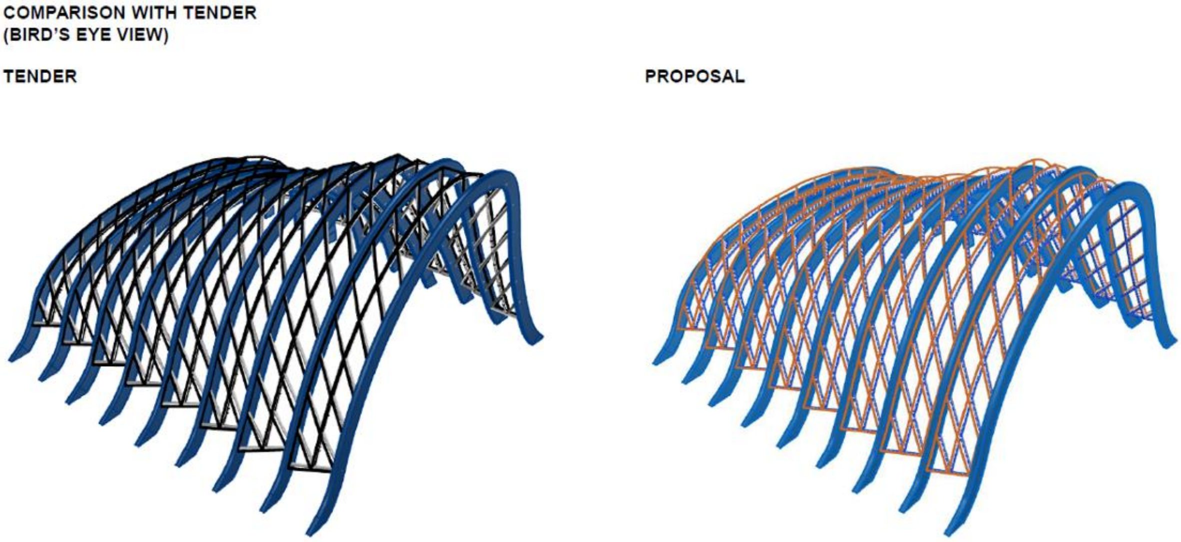

Figure 6: Comparison between 3D tender model and ETFE-types optimized model proposal.

3.2. Kai Tak Sport Park ETFE Canopy (Sport Avenue)

The Sport Avenue Canopy of the Kai Tak Sport Park in Hong Kong is a new iconic rectangular ETFE structure 30m wide and 241m long for a total area of approximately 6,800 m2. The canopy is installed at 30m above the ground between two buildings to cover a pedestrian area dedicated to retail activities nearby the Kai Tak Main Stadium. The ETFE structure is made of 96 triangular cushions, most of them 6m wide and12m long, supported by a steel structure. The complexity of the design is given by the high wind loads (up to ~5kpa) that has required special analysis of the ETFE performance and the addition of stainless steel cables on both lower and upper layer of the ETFE to increase the resistance (Figure 7).

Figure 7: Render Views of the Sports Avenue ETFE Canopy.

The Sport Avenue Canopy project illustrates the effective utilization of parametric design methodologies to address architectural challenges and streamline the design process. Despite being a structure of relatively straightforward complexity, the parametric environment was fully justified by the swift responsiveness it offered in design decision-making. This highlights that parametric design is not merely reserved for specialized cases but is instead a best practice for ensuring design quality and efficiency. Rhino/Grasshopper played a pivotal role in capturing project inputs and facilitating iterative design exploration within a parametric framework. The seamless transition to Straus for FEM analysis, facilitated by the FeMM plugin, underscores the interoperability between different digital ecosystems within the OSM framework. This interoperability enables efficient collaboration and exchange of information across various stages of the design process from conceptualization to structural validation (Figures 8, 9).

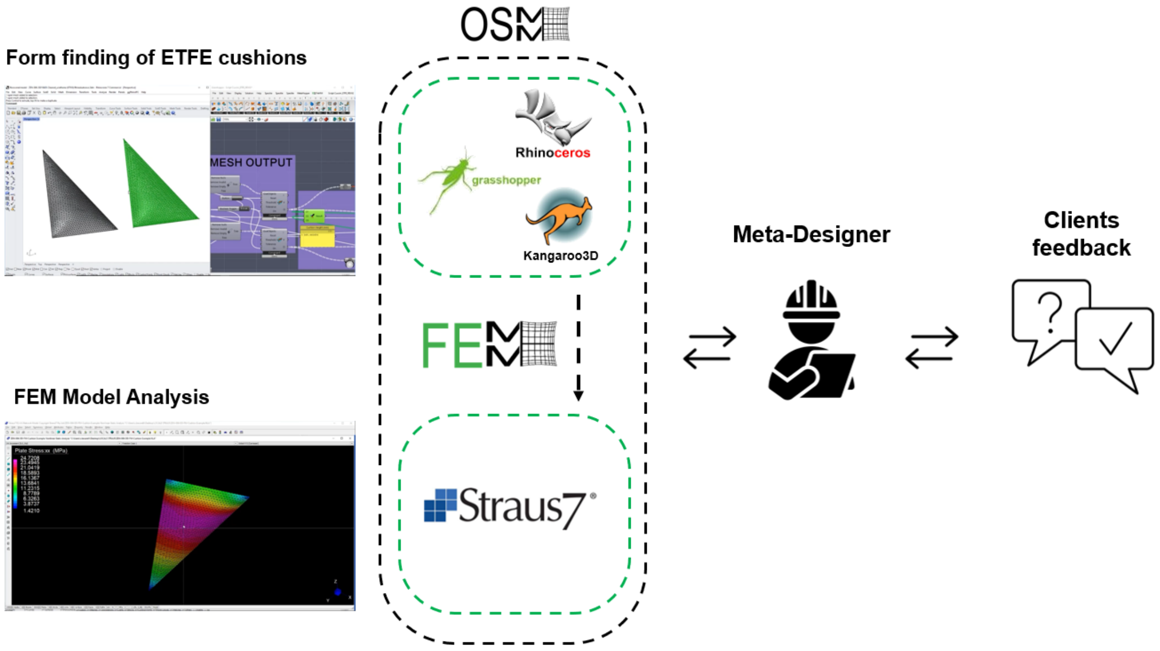

Figure 8: Conceptual scheme of pipeline of work for Kai Tak’s Sport Avenue Canopy. The connection between parametric and FEM analysis digital environments allows the meta-designer to interact with the client, acknowledge feedback, and reiterate the design process to achieve the set goals.

Figure 9: On left: installation of aluminum profiles and first ETFE membranes. On right: completed installation of pre-inflated membranes.

4. Conclusions

The One Single Model methodology coupled with the Meta-Designer concept represents a paradigm shift in the AEC sector addressing key challenges and harnessing the potential of computational design to tackle complex architectural and engineering problems. The OSM approach streamlines workflows and fosters interdisciplinary collaboration enabling design teams to navigate intricate design processes with precision and efficiency. By integrating all aspects of the project within a unified parametric framework, the OSM ensures transparency, iteration, and responsiveness to client needs throughout the design process. The Meta-Designer concept empowers all team members to contribute to the design process leveraging their diverse expertise to create innovative and sustainable solutions. This collaborative approach not only enhances the quality of outcomes but also fosters a culture of continuous learning and improvement within the team. As exemplified through real-world applications in free-form structures with membranes, the OSM methodology enables the seamless integration of form-finding, optimization, and fabrication processes ensuring the realization of architectural visions while meeting project objectives. In an era marked by increasing reliance on AI for architectural concept generation, the OSM framework provides a human-centered approach that prioritizes client needs, interdisciplinary collaboration, and design excellence.

References

[1] M. S. V. de Souza and R. M. O. Pauletti. A computational framework for the design of tensile structures. *Advances in Computational Science and Engineering*, 2(1): 37-72, 2024.

[2] B. Füzes and D. Hegyi. Parametric Details of Membrane Constructions. *CAADence in Architecture*, pp. 73 – 78, 2016.

[3] C. Maureira, H. Pinto, Hernán & Yepes, J. Victor & Garcia Conejeros. Towards an AEC-AI Industry Optimization Algorithmic Knowledge Mapping: An Adaptive Methodology for Macroscopic Conceptual Analysis, *IEEE Access*, 9, pp. 110842 – 110879, 2021.

[4] A. Maksoud, B. Al-Beer, A. Hussien, S. Dirar, E. Mushtaha and M. Yahia. Computational Design For Futuristic Environmentally Adaptive Building Forms And Structures. *Architecture and Engineering*, vol. 8, 2023.

[5] R. Mikaelsson. Computational Design in the AEC industry : Applications and Limitations. *Master thesis in Architectural Engineering at Luleå University of Technology*. 2022.

[6] D. Holzer. BIM and Parametric Design in Academia and Practice: The Changing Context of Knowledge Acquisition and Application in the Digital Age. *International Journal of Architectural Computing*. 13, pp. 65-82, 2015.

[7] A. Indraprastha. Encouraging Computational Skills: Evaluating BIM Course to Support Design Studio. *Proceedings of the EduARCHsia & Senvar 2019 International Conference (EduARCHsia 2019)*, pp. 194 – 201, 2020.

[8] L. Sattler, S. Lamouri, R. Pellerin & T. Maigne. Interoperability aims in Building Information Modeling exchanges: a literature review. Proceedings of the *9th IFAC/IFIP/IFORS/IISE/INFORMS Conference on Manufacturing Modelling, Management and Control (IFAC MIM 2019), Berlin, Germany. IFAC-PapersOnLine*, 52(13), pp. 271-276, 2019.

Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine De Wolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Copyright Declaration

Before publication of your paper in the Proceedings of the IASS Annual Symposium 2024, the Editors and the IASS Secretariat must receive a signed Copyright Declaration. The completed and signed declaration may be uploaded to the EasyChair submission platform or sent as an e-mail attachment to the symposium secretariat (papers@iass2024.org). A scan into a .pdf file of the signed declaration is acceptable in lieu of the signed original. In the case of a contribution by multiple authors, either the corresponding author or an author who has the authority to represent all the other authors should provide his or her address, phone and E-mail and sign the declaration.

Paper Title: Unlocking Architectural Potential: The Synergy of One Single Model and Meta-Designer in Parametric Innovation

Author(s): Federico Mario La Russa, Antonio Diaferia

Affiliation(s): Maffeis Engineering

Address: Via Mignano 26, Solagna (VI), Italy

Phone: +39 0424 558361
E-mail: a.diaferia@maffeis.it

I hereby license the International Association for Shell and Spatial Structures to publish this work and to use it for all current and future print and electronic issues of the Proceedings of the IASS Annual Symposia. I understand this licence does not restrict any of the authors' future use or reproduction of the contents of this work. I also understand that the first-page footer of the manuscript is to bear the appropriately completed notation:

> *Copyright © 2024 by <name(s) of all of the author(s)>*
> *Published by the International Association for Shell and Spatial Structures (IASS) with permission*

If the contribution contains materials bearing a copyright by others, I further affirm that (1) the authors have secured and retained formal permission to reproduce such materials, and (2) any and all such materials are properly acknowledged by reference citations and/or with credits in the captions of photos/figures/tables.

Printed name: **Antonio Diaferia**
Signature:
Location: Solagna (VI), Italy
Date: 24/06/2024