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Conceptual design of tensile membrane structures using interactive optimization

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Abstract

The design of any structure typically involves three main steps: conceptualization, analysis, and design. In conventional structures, the conceptualization or conceptual design step relies on a designer's choice, significantly determining the design and behavior of the final structure. Tensile membrane structures (TMS) are known for their aesthetic appeal, efficiency, and extensive design flexibility. However, conceptualizing a TMS poses different challenges as the initial shape is unknown and needs to be form-found. This makes the conceptual design stage for TMS more challenging, as each following step in the design process has to be integrated with the others. To address this challenge, this study employs an integrated interactive evolutionary framework, designed to assist the designer in exploring diverse TMS shapes. The framework is developed to handle different TMS types, with various support types and boundary conditions. This empowers the designer to explore a range of TMS shapes starting with only an initial input domain. Notably, the proposed framework also enables designers to select their preferred TMS shapes to guide the evolutionary design process. The designer also has the flexibility to introduce different constraints to the input domain, restricting the explored design space. The overall study is illustrated with various TMS case studies, showcasing the adaptability of the framework to TMS with different boundary conditions and support types.

Keywords: tensile membrane structures, conceptual design, interactive optimization, generative design

1. Introduction

The process of designing any structure involves several iterative phases: conceptualization, structural analysis, and optimization (Brown *et al.* [1]). The conceptual phase marks the beginning of exploration, focused on generating alternatives that fulfill both engineering and architectural criteria. During this stage, decisions are made regarding the overall shape, topology, material and construction which significantly impact the structural performance and usability of the structure (Turrin *et al.* [2]). Various studies have focused into the field of integrated design exploration, which allows for a seamless connection across these different design steps for quick design prototyping. These studies have been implemented for a variety structures, such as shells like structures (Hens *et al.* [3], von Buelow [4], and Marbaniang *et al.* [5]), trussed roofs and buildings (Turrin *et al.* [2] and Clune *et al.* [6]) encompassing aspects like floor plans and structural topology. One approach in integrated design exploration is to allow designers to actively be involved in guiding the design generation (Mueller and Ochsendorf [7]). Interactive approaches enable designers to interactively steer the design exploration within an optimization or generation loop. This is done by leveraging evolutionary optimization algorithms that allow for an interactive exploration of feasible designs. In this process, designers replace conventional utility functions allowing for other desirable solutions to be found (Bletzinger [8] and Adriaenssens *et al.* [9]). The user can also steer the design exploration by modifying the evolutionary algorithm parameters (Evins [10], Mueller and Ochsendorf [7], and Turrin *et al.* [2]).

Tensile membrane structures (TMS) are often chosen to cover large areas as they do not require intermediate supports as they are light-weight, in addition to their aesthetics and efficiency. Unlike more conventional rigid structures (steel, concrete, or timber), the design of TMS is different because its initial stable shape is not known beforehand and must be found through a step called "form finding" (Marbaniang *et al.* [11, 5]). This makes the conceptual stage for TMS more challenging as the initial shape has to be found, numerically or otherwise. The structural performance of TMS is also highly dependent on their geometrical shapes, showing the importance and significant of the initial design stage.

This study presents and outlines a framework that enables the exploration of different TMS shapes during the conceptual phase, incorporating both qualitative and quantitative performance goals. This addresses the challenges that are present in generative methods for TMS, due to the complexity of its analysis and design processes. Sec. 2. gives an introduction to form-finding and parameterization of TMS shapes. In Sec. 3., the interactive optimization framework is developed. Finally, the proposed method is illustrated with the help of case studies in Sec. 4. and concluded in Sec. 5..

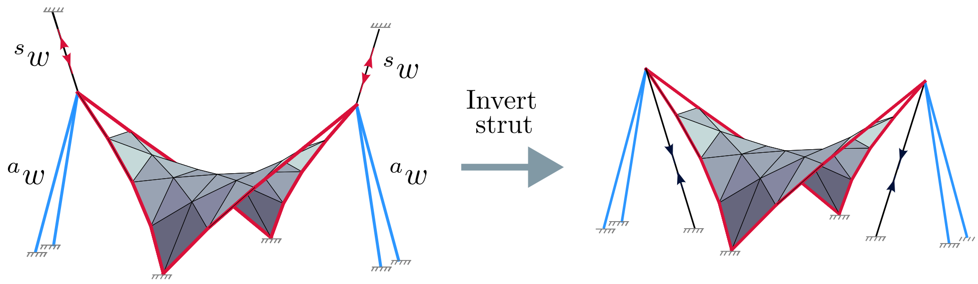


Figure 1: Inverted strut method for form-finding

2. Form-finding and parameterization

2.1. Form-finding using the updated weight method

In this study, the updated weight method (UWM) (Marbaniang *et al.* [11]), is used for finding the initial equilibrium shape for an applied prestress and boundary condition. In UWM, a weighted optimization formulation is given where the weights are related to the applied membrane prestress and cable force. Form-finding of TMS having compressive strut and achorage supports can also be performed using UWM with the simplified inverted-forces approach (Marbaniang *et al.* [12]). The internal forces and geometry of the pseudo-struts are inverted to obtain the actual equilibrium (Fig. 1). Through this approach, adjustments in strut weights can lead to changes in height, as demonstrated in Fig. 2. The generalized form-finding problem is thus defined as a minimization problem:

$$\mathbf{x}^* = \underset{\mathbf{x}}{\text{argmin}}\ f_{UW} = \sum_{i=1}^{N_m}\sum_{j=1}^{3} W_i^j (L_i^j)^2 + \sum_{i=1}^{N_c} {}^c w_i ({}^c l_i)^2 + \sum_{i=1}^{N_a} {}^a w_i ({}^a l_i)^2 + \sum_{i=1}^{N_s} {}^s w_i ({}^s l_i)^2 \tag{1}$$

In Eq. 1, $\mathbf{x}^*$ represents the coordinates of the form-found shape, while W_i^j and L_i^j denote the weight and the jth side length ($j = 1, 2, 3$) respectively, of the ith element. Similarly, ${}^c w_i$, ${}^a w_i$, and ${}^s w_i$ represent the weights, and ${}^c l_i$, ${}^a l_i$, and ${}^s l_i$ represent the lengths for boundary cables, anchorage cables and strut elements, respectively. These weights are found from the target design internal forces through the following expressions:

$$W_i^j = \frac{t_i^j}{2L_i^j}; \qquad {}^c w = \frac{{}^c n}{2({}^c l)}; \qquad {}^a w = \frac{{}^a n}{2({}^a l)}; \qquad {}^s w = \frac{{}^s n}{2({}^s l)} \tag{2}$$

where, t_i^j is the side force (found from a target prestress $\boldsymbol{\sigma}^0$) along the jth side of an ith membrane element (Marbaniang *et al.* [11]). The comprehensive implementation process and algorithms for UWM can be found in (Marbaniang *et al.* [11, 12]). Adjusting the weights of the struts or anchorages will respectively raise or lower the structure's height (and vice versa), as illustrated in Fig. 2, where increasing the strut weight leads to a corresponding increase in height at that particular location.

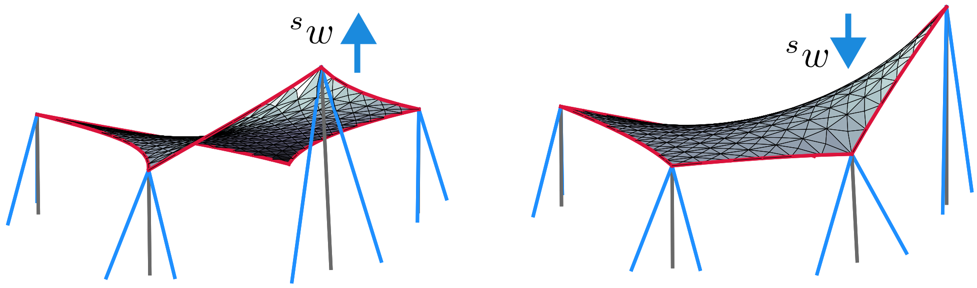


Figure 2: Parameterizing the TMS shape

2.2. Parameterization of TMS shapes

The parameterization of TMS shapes begins by discretizing an input domain Ω given by a designer with boundary $\delta\Omega$. The boundary can be further sub-divided to different edges $\mathcal{E}$ and vertices $\mathcal{V}$ by the designer. The whole domain is then meshed using triangular membrane elements, while the boundary is meshed using line elements. The meshed edges $\mathcal{E}$ can be assigned with cable or rigid frame-support types. In the case of cable assigned edges, the nodes are unconstrained, while the cable line elements are assigned along the cable supported edge. For frame-supported edges, however, the nodes along the edges are constrained, with the nodal co-ordinates fixed at prescribed values. Furthermore, the nodes located at the vertices can also be assigned with struts and anchorage cables. Furthermore, vertex nodes located at frame-supported edges are assigned a height value. The height profile of the frame-supported edge is then interpolated between the assigned heights of the vertices at each end. The parameterization of the ith generated TMS shape is given by the variable $\mathbf{s}$, defined as

$$\mathbf{s}_i = \begin{bmatrix} \mathbf{b} & \mathbf{c}^v & \mathbf{h} & {}^a\mathbf{w} & {}^s\mathbf{w} \end{bmatrix} \tag{3}$$

where, $\mathbf{b}$ defines the boundary support types (cable or frame supported) for all edges, $\mathbf{c}^v$ defines the vertex support condition whether the vertices are fixed in space or strut-supported, $\mathbf{h}$ defines the heights of the vertex nodes (in the case of frame-supported edges), ${}^a\mathbf{w}$ and ${}^s\mathbf{w}$ are the weights for the anchorage and strut elements. The boundary $\mathbf{b}$ and the vertex support condition $\mathbf{c}^v$ are arrays with binary elements to define the boundary support and vertex support condition, given as

$$b_i = \begin{cases} 0 & \mathcal{E}_i \text{ is frame} \\ 1 & \mathcal{E}_i \text{ is cable} \end{cases} \tag{4}$$

$$c_i = \begin{cases} 0 & \text{is fixed-supported} \\ 1 & \text{is strut-supported} \end{cases} \tag{5}$$

The vertex heights $\mathbf{h}$ and weights $\mathbf{w}$ are assigned continuous values, assigned within defined bounds. For every solution $\mathbf{s}_i$, the corresponding form-found shape $\mathbf{x}_i$ is found using the methodology given in Sec. 2.. The form-finding is done by minimizing Eq. 1 for a meshed domain defined by solution $\mathbf{s}$, and a particular target prestress σ^0 and boundary cable force ${}^c n$.

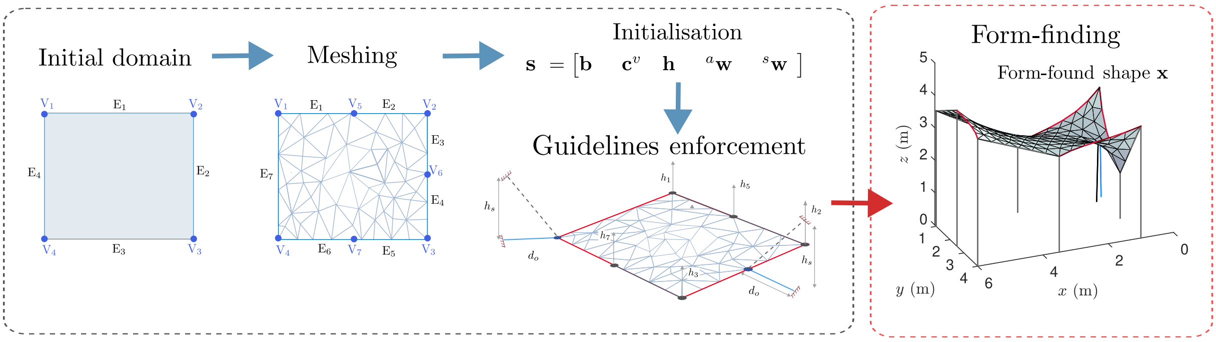


Figure 3: Schematic of TMS parameterization

2.3. Generative guidelines

A generated unique solution $\mathbf{s}_i$ contains randomly generated values for $\mathbf{b}$, $\mathbf{c}^v$, $\mathbf{h}$, ${}^a\mathbf{w}$ and ${}^s\mathbf{w}$. The values however should result in meaningful TMS shapes. This is maintained by the following guidelines:

1. Frame-supported edges with $b = 0$ have all nodes including the vertex nodes assigned with a fixed support condition ($c = 0$). The heights are linearly interpolated from $\mathbf{h}$ given at the vertex nodes. The frame-support edge is assigned with beam elements, with additional vertical members added at each vertex node connecting it to the ground level.

2. Vertex nodes on cable supported edges with $b = 1$ are assigned either with a fixed-support condition $c = 0$ or a strut-support condition $c = 1$. The remaining nodes on the edges, excluding the nodes at the vertex are assigned with a free support and therefore unconstrained. In the case of strut supported vertex nodes, nodes for the anchorage and pseudo-strut elements are introduced normal to the edge at a distance of d_o. The weight variables $\mathbf{w}$ are assigned to these elements during form-finding.

3. The form-found solution for a trial solution $\mathbf{s}_i$ is taken to be feasible if it is not a flat solution, which is ensured by limiting the variation of the co-ordinates is above a certain threshold. Furthermore, the tangent matrix should be positive-definite, ensuring that the form-found shapes are stable.

3. Interactive optimization conceptual design

In this section, an evolutionary algorithm (Deb [13]) is adopted to generate a diverse set of solutions $\mathcal{S}$ that represent different TMS shapes for an input domain given by the designer. In interactive optimization, the selection of the parent solutions $\mathcal{S}_P = [s_1 \dots s_p]$ that are used for generating the next offspring generation $\mathcal{S}_N = [s_1 \dots s_{N_n}]$ is chosen by the designer. The selected parents are then crossed and mutated resulting in a set of diverse solutions with respect to both selected parents. Each solution $\mathbf{s}_i$ comprises of both binary and continuous variables. The offspring solution from two parent solutions from $\mathcal{S}_P$ is generated while following the generative guideline (Sec. 2.3.). Furthermore, the final offspring set $\mathcal{S}_N$ is then ranked and shown to the designer to select, with the process iterated until the shape is finalized.

3.1. Ranking

The generated offspring solutions at each iteration are ranked and then presented to the designer. The designer then uses their qualitative judgments to select the parent solutions. The solutions can also be ranked using quantitative metrics that rank the solutions with a more traditional ranking criteria. This is done so that the number of visible solutions to the designer are reduced.

1. *Diversity*: The generated solutions in $\mathcal{S}_N$ are ranked by diversity, by finding the difference in their form-found shape. The difference between two solutions $\mathbf{s}_i$ and $\mathbf{s}_j$ is given as

$$D_{ij} = ||\mathbf{x}_i - \mathbf{x}_j|| \tag{6}$$

   Finally, the diversity $\mathcal{F}_i^D$ of solution $\mathbf{s}_i$ from all the other solutions in $\mathcal{S}_N$ is measured as

$$\mathcal{F}_i^D = \sqrt{\sum_{j=1}^{N} D_{ij}^2} \tag{7}$$

2. *Cost*: The solutions in $\mathcal{S}_N$ can also be ranked using quantitative metrics, *e.g.*, the total cost $\mathcal{F}^C$. The cost for a solution $\mathbf{s}_i$ can be found by finding its total material weight:

$$\mathcal{F}_i^C = \sum_i^{N_m} A_i t \rho_m + \sum_i^{N_c} {}^c a_i {}^c l_i \rho_s + \sum_i^{N_a} {}^a a_i {}^a l_i \rho_s + \sum_i^{N_s} {}^s a^s l_i \rho_s + \sum_i^{N_f} {}^b a^b l_i \rho_s \tag{8}$$

   where, t represents the thickness of the membrane, while ${}^c a$, ${}^a a$, ${}^s a$, and ${}^b a$ denote the cross-sectional area of boundary cables, anchorage cables, strut members, and boundary frame elements, respectively. The densities of the fabric and steel materials are indicated by ρ_m and ρ_s. In calculating Eq. 8, the optimal element cross-sectional areas against the developed internal forces are found.

3.2. Interactive evolutionary optimization

The proposed evolutionary framework is based on common operations widely used in genetic algorithms and other evolutionary concepts (Deb [13]). The interactive evolutionary algorithm consists of the following steps:

1. *Initialization*: The initial population set $\mathcal{S}_0$ is generated using random inputs for the input domain. Each value in $\mathbf{s}_i$ is however bounded by predefined values given by the designer. The generated solutions are then ranked using the metrics given in Sec. 3.1.. The designer then chooses their preferred parent solutions $\mathcal{S}_P$.

2. *Cross-over*: Two parent solutions from $\mathcal{S}_P$ under cross-over operations. The cross-over operations are done separately for the integer values (boundary and support condition) and continuous values (height and weights). The cross-over operation is dependent on parameter p^c which is used to control the probability of two parent solutions crossing-over.

3. *Mutation*: A mutation step is then followed in order to include random diversity to the solution set. The mutation operation is similarly separately done for the integer and continuous values. In the case of the $\mathbf{b}$ and $\mathbf{c}$, random selected indices for the offspring solution are replaced with different values. For continuous variables, a zero mean Gaussian random error is added to $\mathbf{h}$ and $\mathbf{w}$. A mutation parameter m is used to control the probability and deviation of the mutated solutions from the parent values.

4. *Guidelines and ranking*: Each offspring solution is then processed using the guidelines given in Sec. 2.3.. In case the generated offspring solution is feasible, the solution is then added to $\mathcal{S}_N$ if it has a lower cost than the other solutions present in $\mathcal{S}_N$. The offspring set $\mathcal{S}_N$ is then ranked and sorted. The whole process is iterated until a number of N_s iterations is completed and the generated ranked offspring generation is complete. Note that the ranked offspring set $\mathcal{S}_N$ contains a reduced number of N_n solutions ($N_n < N_s$) shown to the designer. The ranked offspring set $\mathcal{S}_N^i$ is used to denote the ith offspring generation.

5. *Interactive selection*: The ranked offspring solutions are then shown to the designer, who chooses the parent solutions $\mathcal{S}_P$ used for generating the next offspring solution set. This process is iterated with the generation of successive offspring generations until the final desired shape is found.

3.3. Framework implementation

The interactive generative process, is carried out using a visual (GUI) and a text-based prompt interface. The overall steps of the full framework is given as follows:

Step 1: The designer uses a GUI interface to initialize an input domain. The designer can then sub-divide edges further, to increase the parametric design space.

Step 2: An initial population set $\mathcal{S}^0$ is initialized and within bounds already defined by the user. The initial population is ranked based on metrics according to the user's preference, and shown using a GUI interface.

Step 3: The designer selects the parent population set $\mathcal{S}_P$ from initial ranked population set.

Step 4: Two parent solutions from $\mathcal{S}_P$ undergo cross-over and mutation operations. Only solutions that are feasible, having a lower fitness value are added to $\mathcal{S}^i$.

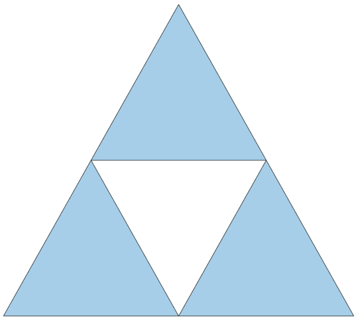
Step 5: Step 4 is repeated until the maximum number of iterations N_s is reached.

Step 6: The offspring generation $\mathcal{S}^i$ is shown to the designer and Step 3 is repeated until the final desired shape is obtained.

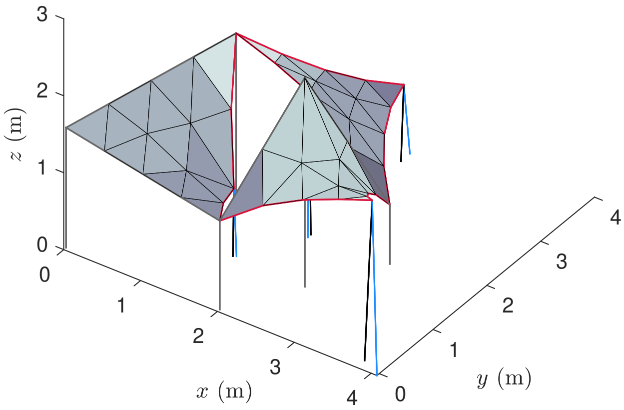
4. Case studies

4.1. Case study 1

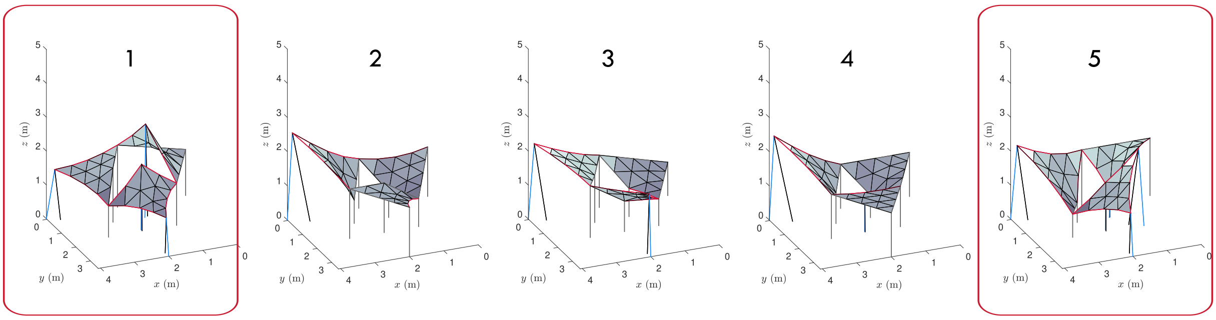
In the first case study, a combination of triangular shapes, as shown in Fig. 4(a), is considered. The selected shapes by the designer are given in red blocks. The initial generation, first generation and second generation are given in Figs. 4(b), (c) and (d). All the shapes are ranked by using the diversity metric $\mathcal{F}^D$. The interactive design following the evolutionary framework developed in Sec. 3. is able to generate a myriad of TMS shapes from the simple input domain given in Fig. 4(d). The final selected TMS shape is given in Fig. 4(b). This case study shows the effectiveness of the proposed method for the interactive conceptual design of TMS shapes.



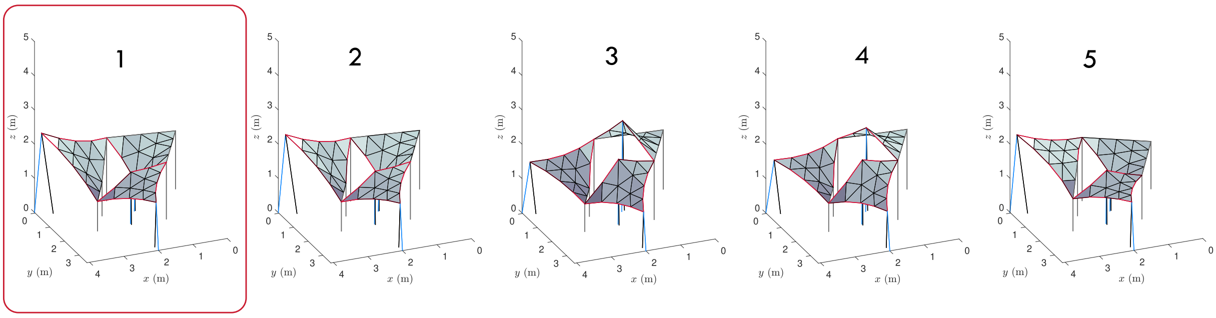
(a) Initial domain



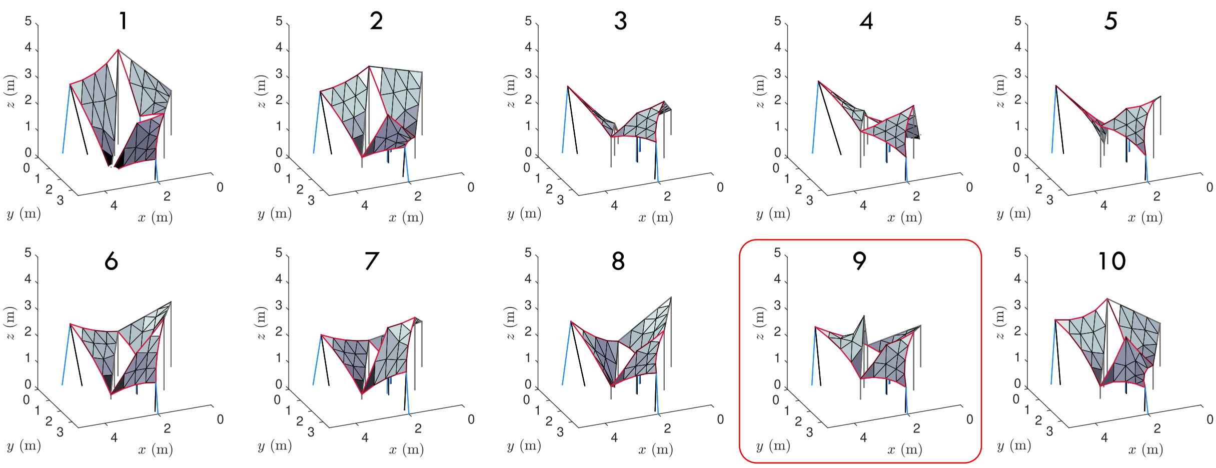
(b) Final shape



(c) Initial generation

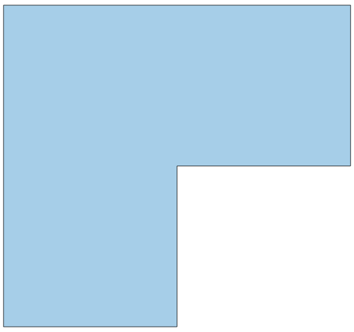


(d) Generation 1

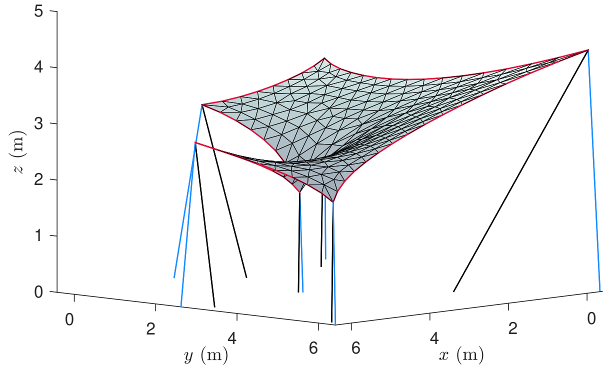


(e) Generation 2

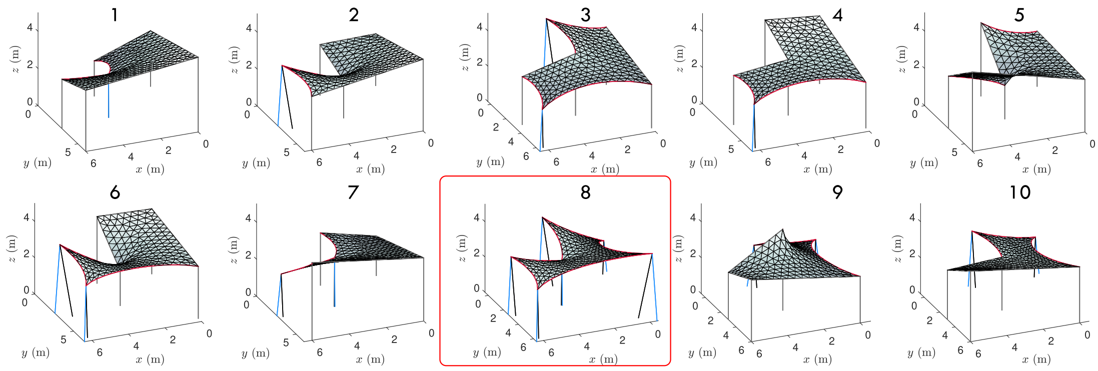
Figure 4: Case study 1



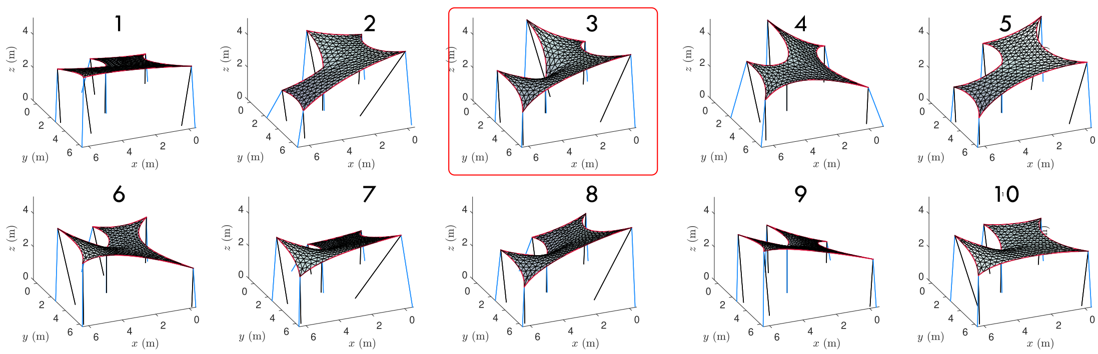
(a) Initial domain



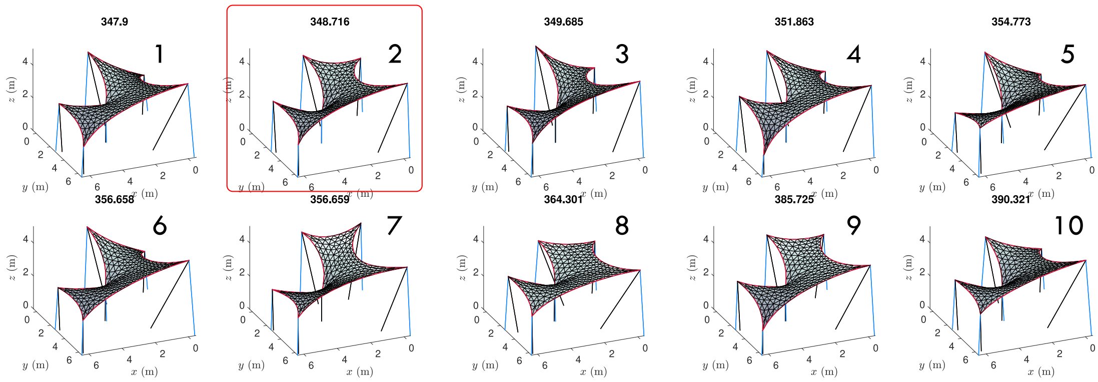
(b) Final shape



(c) Initial generation

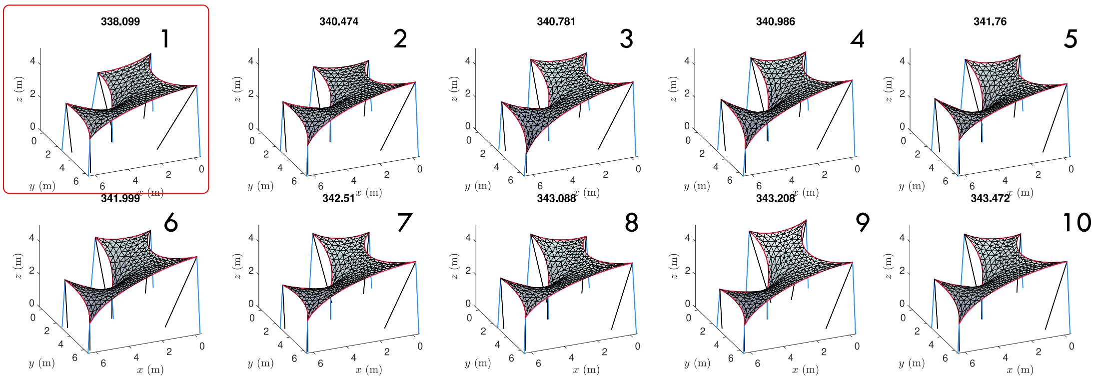


(d) Generation 1



(e) Generation 2

Figure 5: Case study 2



(a) Generation 3

Figure 6: Case study 2

4.2. Case study 2

In this case study, the ranking metrics by which the solutions are ranked are changed after a few generations. Initially the diversity metric ($\mathcal{F}^D$) is used to rank the solutions. After the designer is satisfied with a solution, further optimization of the cost ($\mathcal{F}^C$) is done. This process locally perturbs the solution in finding the optimal weight. However, this is not done significantly to change the structural aesthetics from the initial chosen shape. The initial domain is shown in Fig. 5(a), with the initial, first, second and third generations shown in Figs. 5(c),(d),(e) and Fig. 6(a). The later two generations are ranked by using the cost metric given in Sec. 3.1., with the material cost labeled over each shape. At this stage, the designer chooses the shape with the lowest cost. The final desired shape is shown in Fig. 5(b). This case study highlights the application of both qualitative and quantitative objectives to the interactive optimization process.

5. Conclusion

Tensile membrane structures are used for their attractive aesthetics combined with vast design possibilities, particularly in open areas. This research presents an interactive framework tailored for TMS exploration, empowering designers to experiment and steer the shape generation process. The interactive evolutionary algorithm facilitates the exploration of various TMS shapes, balancing qualitative and quantitative performance metrics, while allowing the designers to maintain control over offspring generation through a selection process. The presented interactive framework is effectively showcased through two case studies involving different TMS types. This developed framework tackles the interactive exploration of TMS, a dimension often overlooked in the majority of design exploration or form-finding studies.

In the future, the work will be developed as open-source plugins for popular tools such as Rhino. This will further increase the overall effectiveness and interaction capabilities with the designer.

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