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Irregular cable-nets: exploring irregularity as a driver for form and structure

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Abstract

Unlike conventional cable-nets that typically use evenly spaced cables laid out in an orthogonal-grid, introducing irregular patterns into the form-finding process of cable structures enables designs with non-directional grids and varying cable concentration. These characteristics are investigated in this paper as a mean of expanding the design space of such systems and of achieving a more equal force distribution in the cable network. A comparison between the structural performance of cable nets with orthogonal and Voronoi cable meshes is performed that evaluates how these different cable arrangements transfer forces within the network and determines the structural mass required by each system to achieve comparable deflections. Furthermore, this paper explores the cable discontinuity characteristic of Voronoi grids as a feature that enables cable section optimization throughout the system. A similar optimization strategy is also applied to orthogonal cable-nets and a study comparing possible weight reduction through section optimization is presented.

Keywords: Cable-net structures, irregular cable mesh, topology, Voronoi, structural simulation

1. Introduction

Cable-net structures were initially introduced in architecture in the 1950's, for the Dortan Arena in Raleigh, and continued to be erected as the primary structural system for many large-span iconic structures until the beginning of the 1990's (Vandenberg [14]). The German pavilion at EXPO 67 and the Olympiapark for the 1972 Summer Olympic Games serve as prominent examples of their lightweight design and ability to convey expressive forms in architecture. Since then, a few cable-net structures have been designed for stadium roof and glass facade projects, but not in the role of main architectural design driver.

Given that cable elements offer no stiffness under compression or bending, carefully-designed arrangements are required to guarantee that cables are tensioned under any load scenario and can provide resistance against wind-induced flutter. One common arrangement is with two transverse sets of cables with opposite curvature, forming an anticlastic surface (saddle), where one set resists downward forces and the other uplift. This evenly-spaced cable set in an orthogonal configuration is referred to in this work as a "standard" or "regular" mesh.

The development of cable structures in architecture was greatly propelled by the work of architect Frei Otto and his collaborators. Frei Otto's design approach used physical models for form finding, using hexagonal cable meshes in the early stages of the design, as pictured in Gass [2], due to their greater flexibility and higher construction tolerance, switching to orthogonal cable meshes once the global shape was defined. The possibility of designing cable networks with irregular meshes are also present in his studies (Otto [9]), noting that for hanging networks, a more equalized force distribution is achieved from cables with different segment lengths.

Although a regular mesh with continuous cables does not offer the most efficient use of all cable elements, it is still the most common configuration of cable-net structures. As well as possessing structural rigidity, it provides standardization for cable clamp spacing and thus the cladding dimensions for fabrication (Barnes and Dickson [1]). New fabrication technologies now question the need for standardization by enabling mass-customization with reduced costs. With this in mind, the purpose of this work is to explore the design potentials and structural behavior of non-regular cable-nets and examine their feasibility for architectural applications.

2. Architectural Applications

Form-finding through model making was a notable part of the development of previously built cable-nets, often due to the lack of computational power. In this project, computer-based form-finding was used to generate study models, enabling faster design iteration.

2.1. Continuity

The directional nature of regular cable meshes introduces geometric constraints which occur depending on layout and change of direction of the flow of the cable-net. As an example, to maintain surface curvature and enable a transition in cable direction, the roof structure at the Munich Olympiahalle was designed as nine distinct modules bordered by edge cables (Leonhardt [4])(Figure 2 left). Irregularity enables integrated transitions in cable direction, allowing for a continuous flow of a single net regardless of the intended formal arrangement or possible variance in cable section (Figure 2 right).

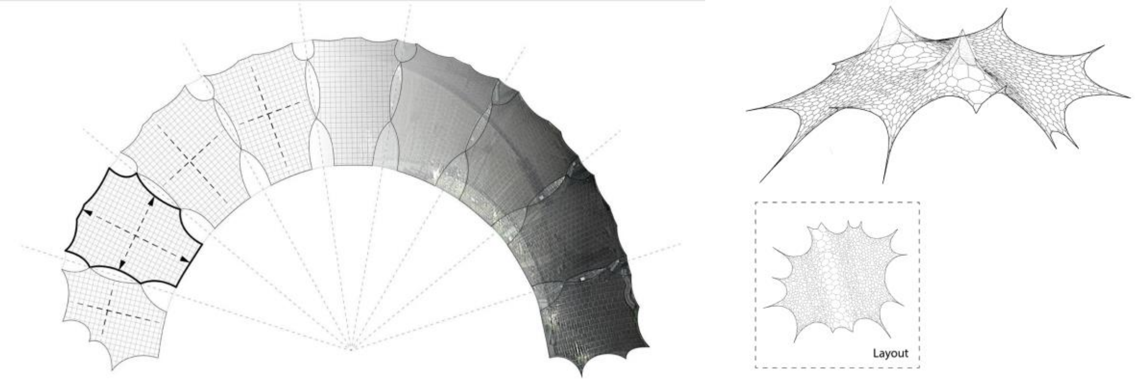


Figure 2: Munich Olympiahalle layout with module and cable direction highlighted (left) integrated transition between two modules showing continuous net (right).

2.2. Geometric Control

By allowing the cable layout to vary, the linear subdivision of the overall geometry is eliminated, allowing for smoother and more gradual transitions of curvature throughout the form. Moreover, varying mesh density around areas of higher curvature allows for a smooth surface approximation with smaller cells introduced only where needed. A set of geometries are generated using the same form-finding conditions and compared showing the approximation with a regular grid, a Voronoi grid, and a Voronoi grid with variable density. As seen in the diagrams (Figure 3), the change of density offers a level of control where areas of lower curvature can afford to have larger cells. In addition, the edge curve can be adjusted by adjusting the edge cells' sizes and numbers.

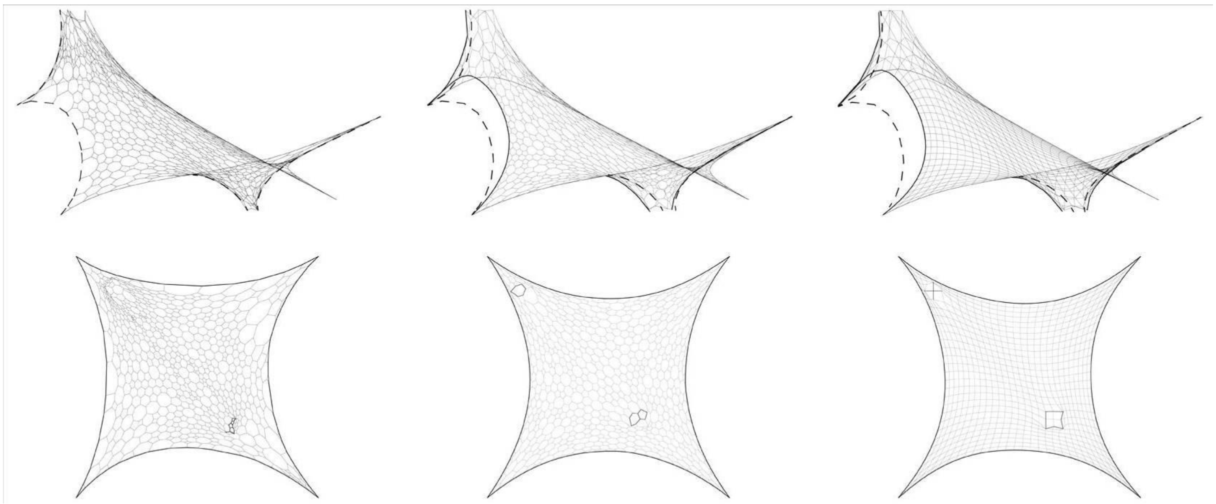


Figure 3: Comparison showing control of geometry using variable net density.

3. Structural Behavior

The majority of published studies regarding cable-nets explore the design and analysis of nets with regular orthogonal meshes, with little information available on the behavior of non-regular orthogonal nets, and non-orthogonal nets and their application. This section evaluates the structural behavior of non-regular orthogonal and Voronoi nets and explores the influence of differential cable concentration in Voronoi meshes.

3.1. Methodology

Given the challenge of exploring various cable-net configurations, requiring form finding the geometry then studying their structural behavior, the cable-nets studied in this section were all designed and analyzed using the Rhinoceros 3D modelling software (McNeel [7]) and its parametric design plugin Grasshopper (McNeel [6]). This combination allows the entire workflow from initial geometry generation, through form-finding to structural analysis to be performed within the same software, providing a fast interface to alter parameters and quickly visualize their effects on the structure's behavior.

Two different forms were explored to compare the behavior of the cable structures: a saddle-shaped net (4 edge supports), and a conical-shaped net (4 edge supports and an inner support) (Figure 4). Both forms were studied orthogonal and Voronoi cable distribution. Since cable elements are structural components that can only withstand tension forces, a top-down design approach to the structural geometry is not possible and the final cable configuration emerges from the force-equilibrium between the different elements, in a process called form-finding. The cable arrangements for these studies are shown in Figure 5. The orthogonal meshes were generated with cable elements set 1 meter apart forming 400 individual cells. A random distribution of points in the same area was used to generate the Voronoi mesh, which also has 400 individual cells.

The distinct elements of these meshes were then transformed into springs with a target length of zero, inducing a prestress state in the structure, and the supports were raised to their final position. The resulting form-found geometry (from the equilibrium between the cable forces and fixed supports) was used as the initial configuration for each study case. This process was developed using Kangaroo, a physics engine for Grasshopper (Piker [12]).

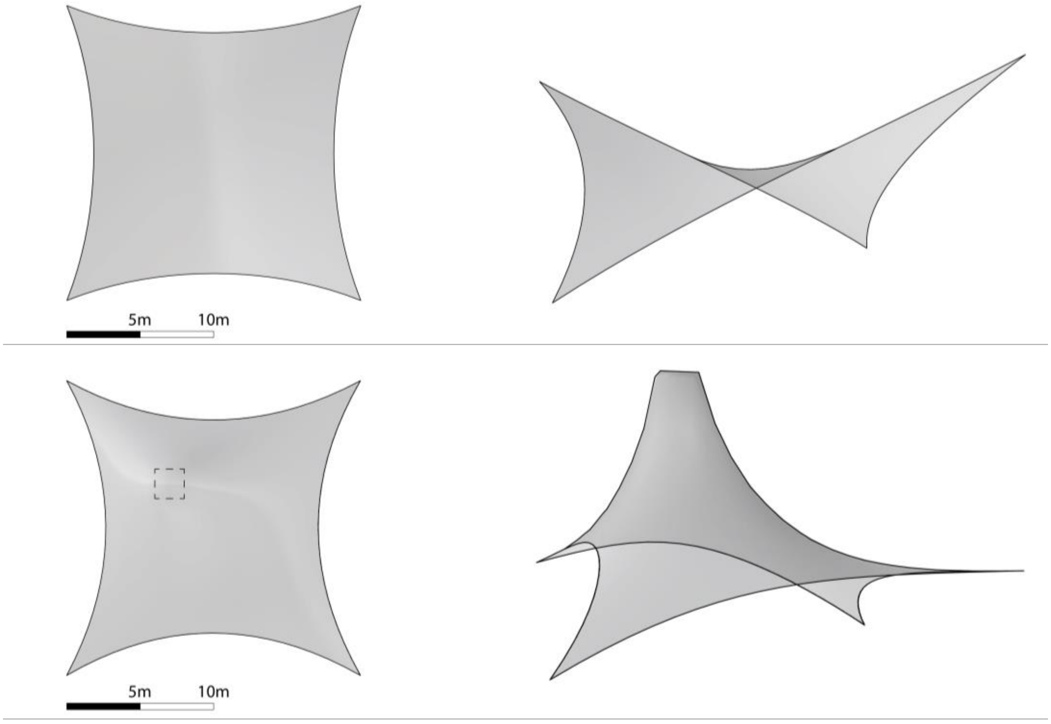


Figure 4: Plan and perspective view of the saddle-shape (top) and conical-shaped (bottom) configurations for the cable-nets

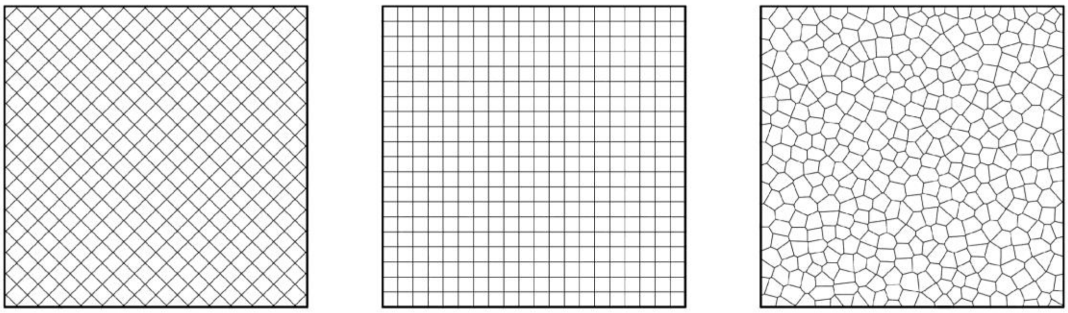


Figure 5: Cable configuration used in the form finding process of the orthogonal (left and center) and Voronoi patterns cable-nets

The structural behavior of the different cable-net configurations was analyzed with Karamba, a finite element solver plugin for Grasshopper (Preisinger [13]). The cables were divided into two groups for cable section attribution, edge cables and inner cables. All topologies were assigned the same vertical load of 0.3 kN/m^2 in both downwards and uplift directions, to represent a cladding or wind load. The self-weight of the cables was also taken into account for the analysis.

Since Voronoi nets are composed of numerous individual cable elements, two methods were studied in order to simplify the prestressing process: prestress by shortening the edge cables only, which consequently stress the inner cables of the net; and prestress induced by applying support displacements at the elevated supports. Both proved to be plausible methods for prestressing the cable network and culminated in similar results.

To consider fabrication aspects in the design and optimization of the structures, the structural models analyzed in this section were all designed with standard commercial stainless steel (AISI 316 / EN 1.4401) cable sections, extracted from the PFEIFER 2015 Catalogue [11]. The structural design was iterated to achieve the lightest cable structure required to meet the specified displacement criteria for each scenario while respecting the maximum utilization allowance for each cable element.

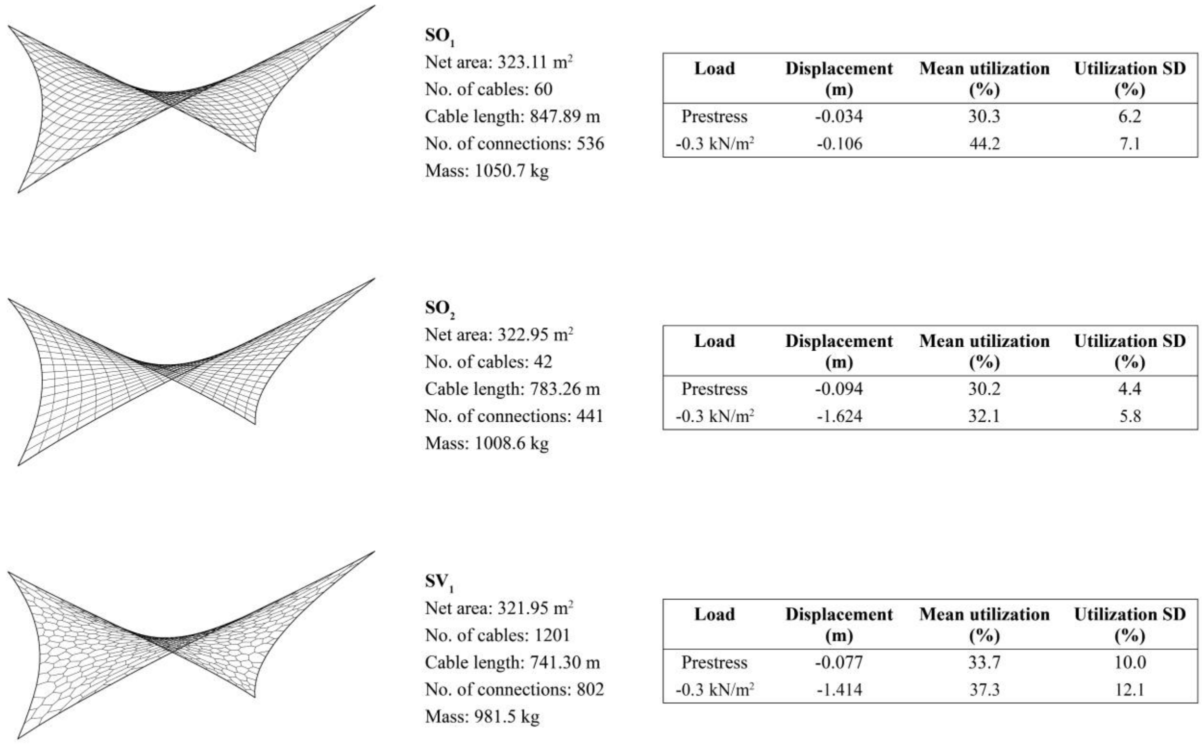
3.2. Performance

3.2.1. Comparison

The structures were first designed considering one constant cross section for the edge cables and another for all inner cable elements.

Three different cable-nets with a saddle shape were designed for structural comparison, one with a Voronoi mesh (SV_1) and two with orthogonal meshes with cable orientation following the principal curvature of the saddle surface and at 45° to it (SO_1 and SO_2 respectively). Identical cable sections and loads were applied to all three models.

As seen in Figure 6, the Voronoi mesh has the smaller total cable length and structural weight of the three nets, but its number of single cables is over twenty times that of the two others and its number of connections is between 1.5 to 2 times higher (Figure 6).



SO_1
Net area: 323.11 m^2
No. of cables: 60
Cable length: 847.89 m
No. of connections: 536
Mass: 1050.7 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.034	30.3	6.2
-0.3 kN/m^2	-0.106	44.2	7.1

SO_2
Net area: 322.95 m^2
No. of cables: 42
Cable length: 783.26 m
No. of connections: 441
Mass: 1008.6 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.094	30.2	4.4
-0.3 kN/m^2	-1.624	32.1	5.8

SV_1
Net area: 321.95 m^2
No. of cables: 1201
Cable length: 741.30 m
No. of connections: 802
Mass: 981.5 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.077	33.7	10.0
-0.3 kN/m^2	-1.414	37.3	12.1

Figure 6: Characteristic and performance of the saddle-shape cable-nets

Regarding the deflection in the nets, Figure 7 show that SO_1 experiences significantly less displacement than SO_2 and SV_1, due to the fact that its cable configuration aligned with the surface's principal curvature has a higher mesh rigidity (Muttoni [8]). The rigidity of SV_1 closely resembles that of SO_2, in accordance with the results presented by Heppel [3].

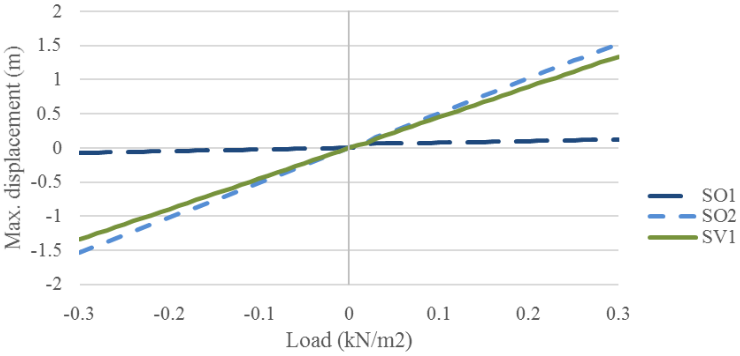
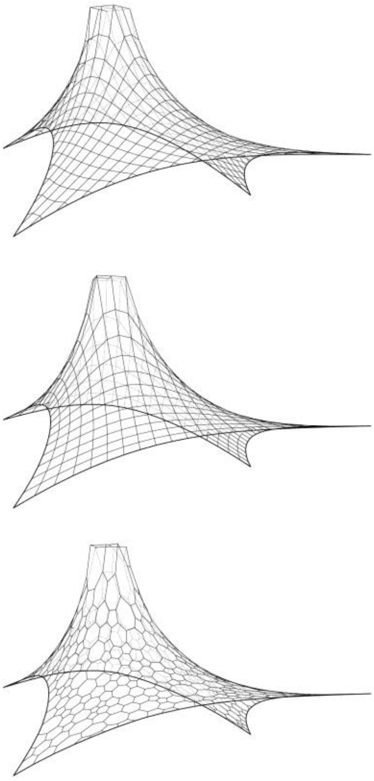


Figure 7: Displacement x load graph of the of the analyzed saddle-shape nets

In addition to the saddle-shape cable-net, a conical-shape configuration of cables was also studied, again with meshes of Voronoi pattern (V_1), and orthogonal pattern with cable directions varying 45° (O_1 and O_2). Similar to the saddle-shape results, the cable-net with Voronoi mesh again shows the smallest global cable length and structural weight, with stiffness also following the same pattern (Figure 8 and Figure 9).



O_1
Net area: 356.57 m^2
No. of cables: 60
Cable length: 896.97 m
No. of connections: 536
Mass: 2104.0 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.036	15.0	7.3
-0.3 kN/m^2	-0.205	16.7	9.28

O_2
Net area: 366.05 m^2
No. of cables: 42
Cable length: 852.55 m
No. of connections: 441
Mass: 2012.7 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.076	15.1	5.4
-0.3 kN/m^2	-0.513	17.5	7.3

V_1
Net area: 364.04 m^2
No. of cables: 1201
Cable length: 771.83 m
No. of connections: 802
Mass: 1856.2 kg

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.080	16.3	6.4
-0.3 kN/m^2	-0.535	17.7	8.2

Figure 8: Characteristic and performance of the conical-shape cable-nets

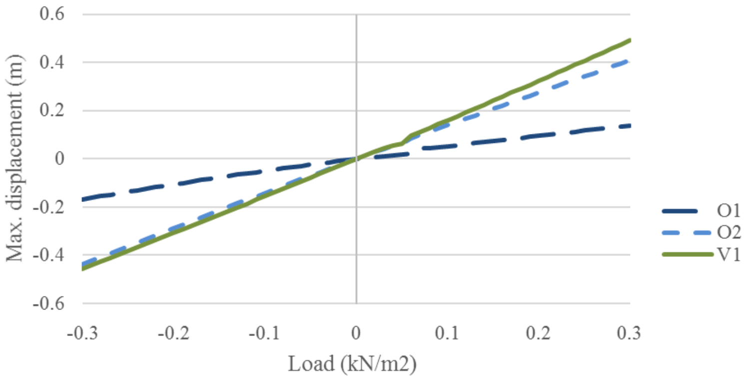


Figure 9: Displacement x load graph of the of the analyzed conical-shape nets

To further investigate the performance of the saddle-shape nets, cable sections and prestress were adjusted with an aim to achieve the lightest structural weight for each configuration while respecting limits of maximum member utilization and satisfying a service requirement of a 0.5 m maximum displacement. The performance of the conical cable-net with orthogonal mesh O_1 again stands out with lower structural weight and displacement value for this configuration, as seen on Table 1.

Table 1: Structural properties and performance of the analyzed conical-shape nets

Mesh	Inner cable Section	Edge cable section	Mass (kg)	Prestress (mm/m)	Max. displacement (m)	Mean utilization (%)
O_1	PE20	PE75	1440.7	1.15	-0.290	26.4
O_2	PE30	PE100	2012.7	1.22	-0.496	22.7
V_1	PE30	PE100	1856.2	1.27	-0.500	21.9

3.2.2. Local segment section optimization

Since Voronoi nets do not exhibit continuous cables, but rather various individual cable segments, they present the opportunity for tailored cable cross-section in order to increase the structural utilization while reducing material consumption. To explore this optimization potential, the previous structures, O_1, O_2, and V_1, were all re-designed maintaining their original cable geometry, support and loading conditions, and 0.5 m maximum displacement, but with variation allowed in the cross sections of the inner cables.

Although a considerable structural weight reduction is achieved by this method, since the standard cable configuration of orthogonal meshes experiences a wide range of forces resulting in many oversized cable segments, the assembly of these structures would increase in complexity due to the elevated cable segment count, approaching that of the Voronoi cable meshes (Table 2).

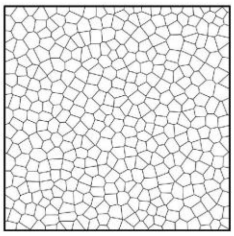
Table 2: Structural properties and performance of the optimized nets

Mesh	No. of Cables	Mass (kg)	Prestress (mm/m)	Max. displacement (m)	Mean utilization (%)
O_1'	900	722.0	1.52	-0.493	71.5
O_2'	840	727.4	1.95	-0.494	79.7
V_1'	1125	869.2	1.82	-0.499	79.1

3.2.3. Cable concentration variation

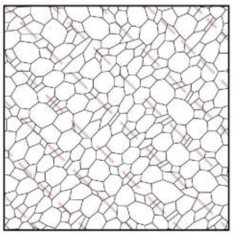
Designing cable-nets with non-regular meshes has the possibility to vary cable concentration throughout the net. In order to investigate if this design freedom could benefit the cable force distribution, extra saddle-shape (SV_2, SV_3) and conical-shape cable-nets with Voronoi meshes (V_2) were designed. The meshes for SV_2 and SV_3 were designed with higher concentration of Voronoi cells following the orientation of the surface's principal curvature, with 90 degree rotation between them (Figure 10), while V5 was designed with a pattern where the Voronoi cells are denser closer to the edge cables and supports, where the nets experiences a higher concentration of loads (Figure 11). This was done by altering the point distribution that generates the Voronoi mesh.

For the purpose of comparison, the structures were designed with the same support conditions and similar net area as the original nets (SV_1 and V_1), and the mean utilization is relative only to the inner cable elements.



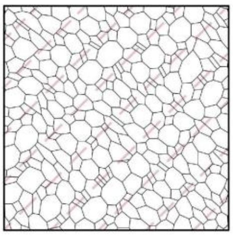
SV_1

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.110	22.3	6.6
-0.3 kN/m²	-1.543	24.8	8.2



SV_2

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.108	21.4	8.1
-0.3 kN/m²	-1.964	24.0	9.8

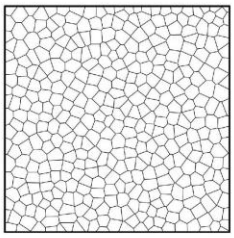


SV_3

Load	Displacement (m)	Mean utilization (%)	Utilization SD (%)
Prestress	-0.110	21.5	8.2
-0.3 kN/m²	-1.801	24.2	10.3

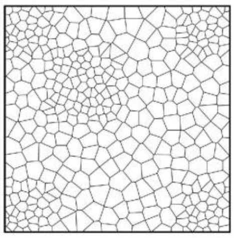
Figure 10: Performance of the saddle-shape nets with different Voronoi cable configurations

As shown, altering cell orientations had a great impact on the behavior of the saddle-shape nets. As for the conical nets, both displacement and utilization had small variations around the original values with little improvement on the force distribution between cables, shown by the lower standard deviation value. This implies that, for the same number of cells, cable concentration can be varied, to a certain extent, across the net to suit design requirements without significant changes in the structural behavior.



V_1

Load	**Displacement (m)**	**Mean utilization (%)**	**Utilization SD (%)**
Prestress	-0.075	17.5	6.8
-0.3 kN/m^2	-0.500	18.9	8.7



V_2

Load	**Displacement (m)**	**Mean utilization (%)**	**Utilization SD (%)**
Prestress	-0.066	16.9	6.2
-0.3 kN/m^2	-0.476	18.4	7.9

Figure 11: Performance of the conical-shape nets with different Voronoi cable configurations

4. Conclusion

The purpose of this work was to explore the feasibility of non-regular cable-nets for architectural applications through an investigation of their structural behavior and design potentials. For this the saddle and conical-shape geometries were studied, as they provide basic forms of tensile structures that can be combined into more complex arrangements, thus providing an overview of the structural behavior of such geometries.

In the case of orthogonal nets with irregular cable spacing, the studied meshes have shown small standard deviation of stress in the cables, indicating that better stress distribution can be achieved in such a system when compared to a mesh with evenly spaced cables. This solution would benefit from modern digital technologies to enable the assembly process for the irregular spacing of cable clamps and the fabrication of non-standard facade panels.

As for the Voronoi patterned meshes, the results show that they do not offer optimal global stiffness for anticlastic shapes. This is possibly due to the planar condition of each three cables sharing the same node, which require a larger deformation to balance out of plane loads. Thus, if structural performance is the main design input, this system could have opportunities as flat nets such as the ones built for cable net walls, which are commonly built to achieve a high degree of translucency for glass facades. In this system, for both cable meshes, stiffness is achieved not through form but primarily through high prestress forces (Mazeika [5]).

On the other hand, where structural performance can be negotiated, irregular cable meshes can be applied to 3 dimensional nets to achieve greater control over curvature and enable continuity, as demonstrated in the second chapter of this paper. This provides a design opportunity to expand current cable-net design space. A trade-off can be made between form and structural performance where an irregular cable-net can provide a design solution that would otherwise not be possible.

Furthermore, although Voronoi-patterned nets require a larger number of elements, an advantage of these discontinuous-cable meshes is the possibility to react to varying cable forces and optimize cable sections over the structure. In addition, because the net behaves like a mechanism, assembly tolerance obstacles common to standard orthogonal meshes are not as dominant in this system, since it can better accommodate for small imperfections, as outlined by Heppel [3].

In conclusion, irregular cable-nets offer the possibility of tailoring cable concentration, allowing new variations of structural form, spatial identity and architectural expression.

5. Acknowledgements

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