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Optimum Selection of a Lattice Central's Tower for a Heliostat's Field

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Authors' contributions

This work was carried out in collaboration between all authors. Authors AVM and JHR designed the study, performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript and managed literature searches. Authors LPR, TLL and JHZ managed the analyses of the study and literature searches. Author ERG has revised the manuscript. All authors read and approved the final manuscript

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ABSTRACT

The lattice structure optimization is based on the modification of three parameters: sizing, configuration and topology. Sizing is about the cross-sectional area of each element, configuration delimits the position of each node and topology is the structural shape that can be made by the position of the elements. The topology is essential in order to obtain not only a minimum weight, but also a structure with an efficient use of its free spaces, with an easy way to be built, with minor costs of production and transportation and with a modular construction. Before the use of a sizing and configuration optimization, the election of the best topology is useful as a pre-optimization.

Thinking about the factors before mentioned, three structural shapes (topologies) were used in mathematical models of steel towers. These three were elaborated with the same requests and total

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loads. The model “A” has the same topology than experimental Solar-Plant in Sonora. The model “B” has a hexagonal shape simulating a double spatial grid. Model “C” has a hexagonal shape with a structure based in lateral restricted frames. The topologies were analyzed by the Mexican constructive steel standards. All models were compare in terms of their solar efficiency, building time, weight, displacement allowed, quantity and length of members, capability of been a modular structure and their characteristics to be optimized. The better topology is the one that uses the hexagonal shape with lateral restricted frames. It has the minimum weight, this has better characteristics to be optimized, members easily of being transportable and better behavior in solar efficiency.

Keywords: Topology; optimization; lattice structure; solar; steel tower.

1. INTRODUCTION

Lattice towers are popular in the design of slender steel structures [1]. An essential purpose of structure design is the optimization of some particular characteristics [2]. There are many important objectives that must be included in the optimization. These ones should be analyzed with an unilateral criteria, with a multi-objective behavior [3]. The principal factor in the optimization is the self-weight [4].

A method that is commonly used to solve searching and optimization problems is the genetic algorithm [5]. The optimization of truss-structures with genetic algorithm can be grouped in three factors: sizing, configuration and topology [6]. In sizing, the cross-section area of the members is changed. In configuration, the localization of the nodes is defined. In topology, the connectivity of the members is searched to find the best one. One of the best considerations to optimize the constructive process and to minimize the problems in the installation is to define the topology of the structure before the optimization.

There are some ways to apply a multi objective optimization. For example, using an undefined topology with a size and configuration optimization [7] or computerizing the optimization problem in order to obtain the best topology using a genetic algorithm [8]. But the computational sources that are spent in the determination of the best topology are bigger than configuration and sizing ones. Rahami [9] uses the force and energy methods to pre-optimize the topology. With this method, knowing the behavior of the structure and the forces in their elements, the principal members and nodes are easily noted. Rodriguez [10] proposes a predefined topology based on the actual structures as a pre-optimization before the use of an optimizing algorithm. He adds the pre-selected topology in the optimization to stablish the best weight.

For obtaining an optimized modular structure the selection of topology is crucial. The selection can be focused in five factors: connections, sizes of pieces for transportation, distances and times in transportation, the costs of using a crane, and the volume of materials [11]. To have a better design of a topology with better conditions, an option is to use a modular configuration. This one has some advantages as the reduction of construction and design times and having the lowest cost [12].

In the optimization of design structures, the weight must not be the only factor to check, also, the addition of the considerations of different kind of members, the problems of the constructions on-site times, and to contemplate easier ways to produce and build the structure should be considered [13]. Considering as a factor in the optimizing algorithm, the extra costs of the construction process for having a theoretical optimized topology can be calculated and added to the final cost of the weight of the structure [14]. This one can be obtained by calculating the number of different types of different members, or using this factor to convert the theoretical topology in one that have some modular characteristics [15].

A crucial point in the optimization of lattice towers is the consideration about the election of the best topology. The obtaining of a theoretical topology could result in a minimum self-weight structure. But the extra costs for problems in the construction times, or the big number of different members would increase the cost, and the final proposal shouldn’t be the best option.

The predefinition of the topology is a better option. But not just considering the actual topologies in the industry, also its needed to considerer modular criteria and think about the possible problems and wastes of time in the construction process.

This paper will present the analysis of the factors that are important to be compared. The comparison will conclude with the obtaining of the best topology. Finally, the conclusions of the methodology and their characteristics of the optimized lattice structure will be shown.

The particular case of lattice tower that will be used in this paper is the central tower of a heliostat's field.

2. THERMO-SOLAR PLANT OF HELIOSTATS FIELD

The thermo-solar plant of central tower is a system dedicated to the capture of solar-energy. This one is transformed into electric energy through the use of a thermodynamic system.

The system is formed by a field of heliostats that re-directs the solar-energy, a receptor that receives and keeps the energy and a central tower that supports and protects the receptor. The elements are shown in Fig.1

Fig. 1. Experimental thermo-solar plant in Sonora, México [16]

Fig. 2. Steel restricted frames of UAQ's tower

Around the world there are many different kinds of towers used as heliostats tower. There is a solar heliostats field in Sevilla, Spain, named PS20. It has a concrete tower of height of 165 mts with a constant section [17].

In United States of America, in the desert Mojave in California, there is the central tower field of heliostats called Ivanpah Solar Electric Generating System [18]. This is a heliostat steel tower with height of 139 mts. The tower has a squared configuration.

In México, the investigations of removable energies are made by the Energies Investigation Center (by its initials in Spanish “CIE”) with the help of universities and other specialized centers. One of the experimental towers made in México is in Sonora [16]. This steel tower has a square base with four identical sides. Central tower of Experimental Solar Field in Sonora has a height of 30 mts. Each level has 6 mts of height, and in the last one there is the equipment for the capture of solar energy. This structural shape is shown in Fig. 1.

In the Autonomous University of Queretaro (UAQ) in the city of Querétaro, México, a hexagonal tower is in its construction process. This tower is made by modules of lateral restricted steel frames. The progress of its construction is shown in Fig. 2 and Fig. 3.

Fig. 3. Concrete Foundation of UAQ's tower

3. METHODOLOGY

To obtain the best topology, pre-optimization criteria will be used. This topology will have characteristics like weight efficiency, high utility in solar energy capture, considerations about building process and constructive times. The initial optimization will be the election of the best topology using only a simple analysis, without any optimization algorithm.

Structuring is a factor that determines the complexity of the constructive process, of the design of the element, the project’s development and the use of the structure. The kind of structure that has all the last characteristics is the lattice one. Some advantages of this one is the modular topology, the use of no-specialized workers, simple connections, easy to transport and a possible low weight.

Three topologies will be chosen to be used as central towers of solar energy of a heliostat field. The behavior of the different topologies will be obtained through their respective mathematical models. The models will be done with the finite element method (FEM), with a linear static analysis and a plastic design of the elements. The three towers will have a height of 30 mts and their base mustn’t be greater than an area of 6x6 mts.

The three topologies will be analyzed and compared between them. Then these ones will be used in a future analysis with an optimization algorithm. In the next sub-chapters, the characteristics and criteria of the comparison and the election of the topologies will be shown.

3.1 Energy Efficiency

Around the world there are different central towers of heliostats that have as a common factor a shape that help the capture of the solar energy. The shape helps in the diminution of the angle between the solar waves (from the heliostats) and the normal direction of the towers faces. When the angle has a zero value, the capture of solar energy is maximum. Because the perpendicular component of the waves (respect the face of the tower) doesn’t exist. In all the figures, the empty arrows represent the solar waves with a zero-degree angle. And the filled ones represent the waves with an angle different from zero.

No matter the position of the tower in the heliostats field, the most efficient shape is the circle one. This one is shown in Fig. 4.

A circular shape is difficult to make because of the high quantity of unions that could have. And because the efforts spend in rolling the steel members in a circular shape.

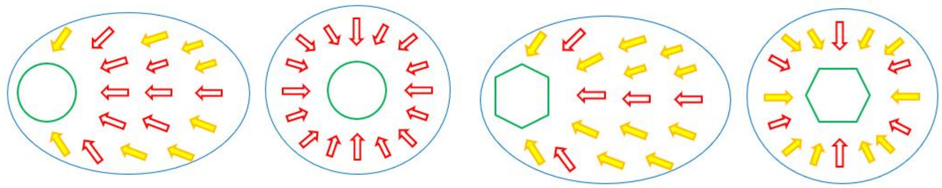

Fig. 4. Energies distribution in circular topology vs polygonal topology

The most practical shape that the tower could have is a hexagonal shape. This one can be appreciated in Fig. 4.

3.2 Modular Capacity

It is important in this study that the structure could be built in an easy and fast way. The tower must have some group members with the same cross-area section and length. For having these characteristics, the best option is a modular structure.

A modular structure makes the tower becomes cheaper than other structures without a modular shape. Modular structuring helps to minimize the quantity of different members, therefore, the fabrication of the elements and their connections become cheaper than the situation when the structure has many different members. The fabrication and building time, the transportation cost and the qualified workers are some of the advantages of a modular structure.

3.3 Transportation and Construction Costs

The costs of transportation (the kind and cost of transportation to be used in moving the materials from the factory to the construction's site area) are included in the unitary cost of the elements' materials. It's important to consider the length and dimensions of the structural members because the size and costs of the transport to be used is an important factor in the final cost. Depending of elements of elements, the transportation could be done in trucks, trailers, or others. The elements with shorter dimensions need smaller trucks. These ones are cheaper, can be driven in more types of roads (with different topographies and with many geographic conditions).

By using a modular structure, the construction process becomes easier than other kind of structures. Besides, smaller members are easy to manage and to be installed by the workers. Large dimensions make difficult the transport of their members, their installation, and probably requires the use of mechanic equipment as cranes.

The kind of connections is important to determine the use of qualified of non-qualified workers (with or without some kind of capacitation). Also, the connections are important to know the dissipation of energy against the dynamic forces (the screwed unions have more energy dissipation than welded ones). Screwed connections have more quantity of materials than welded ones.

3.4 Inner Area Optimization

The chosen topology must have the necessary free inner area for developing the functionality of the tower. It must have the free spaces for the machine room (for the equipment's and the movements of the tower's workers).

The tower must have enough inner area for the colocation of the stairs (to use by the maintenance personnel in ascent and descent of materials). For comfort and security, the use of marine or spiral staircases is not contemplated. Some free space must exist along the height of the tower. It is necessary to upload the heavy materials from the ground level to the machines room.

3.5 Optimization Algorithm

One of the future goals of this work is to make an optimization algorithm of the heliostat since the modular structuring helps in the process of making and algorithm of the structure. To have elements with the same sections, length, height and characteristics is an important factor for making an effective algorithm.

The tower will have some groups of different members (columns, beams, braces and struts) that will interact between themselves. If one of them changes, the others will be affected. This interaction justifies the use of an optimization algorithm.

4. MATHEMATICAL MODEL

The analysis will be static and will be done through the power and energy theorem. An approximation with the FEM will be done, using real values. The behavior will be ruled with a discrete model using the stiffness method Eq. (1).

$$\int_{\Gamma} [N]^T P \, d\Gamma + \int_{Vol} [N]^T \{\underline{b}\} \, dVol = \int_{Vol} [B]^T [D] \; [B] \, dVol \, \{U\} \qquad (1)$$

Where:

- [N]: shape functions matrix.
- $P = \widetilde{S}\,n$; $\widetilde{S}$: Piola − Kirchhoff tensor
- Γ : border values.
- $\{\underline{b}\}$: body forces vector.
- $[B]$: derivatives matrix of shape functions.
- Vol: Solid volume.
- ρ : Material density.

A commercial program will be used in the creation of the mathematical models. The program used will be the SAP 2000 V16, with its design module using the AISC LRFD 99. Some factors and considerations will be manually changed in this program to update its design module to the AISC LRFD 2016. This standard will be used because the Mexican standard is based in AISC LRFD.

4.1 Mexican Standards Requests

The loads combinations will be obtained from the Federal District of México City Construction Standards [19]. The load combinations will be shown in the Table 1.

Where: D is about the dead loads. Lm is the maximum live load. La is the accidental live load. Wx is the wind in “x” direction. Wy is the wind in “y” direction. Ex is the earthquake in “x” direction. Ey is the earthquake in “y” direction.

The models will be ruled in service and design conditions by the before mentioned construction standards [19]. The permissive lateral displacements specified in the Mexican standards is 0.005 times the difference of its height (30 meters) when there aren’t elements beside the tower that could be damage with the displacement. The permissive lateral displacement will be 15 cms. For having a good behavior in the reception panel, the maximum displacement allowed is 10 cms.

As design criteria all the elements will work with a bigger efficiency than 80% of their total capacity. An exception could be done when a lower efficiency in some elements results in a lower global weigh of the tower. And a modular configuration must be prioritized against a structure efficiency.

4.2 Live and Dead Loads

The same considerations and the same loads will be used in the mathematical models to obtain the results for the best comparison. For initial considerations, the loads of machine room among other will be obtained by the UAQ’s design project of the construction of a heliostat field in its Juriquilla’s Campus.

The kind of elements to be used in the models will be PTR’s and HSS’s sections. This kind of sections were used in the heliostat’s tower in campus Juriquilla. The total area of the tower will be inside a square section of 6 mts x 6 mts. The slenderness factor must have a maximum value of five. With this value the tower won’t have dynamic amplification in it’s wind’s effects. The tower will have height of 30 meters.

In the mathematical models the self-weight shall be include. In the top level’s tower will be the machine room. This one will have the equipment that transform the solar energy in electric one. All the equipment has in sum a weigh of 2 Tons, distributed in all the effective floor of the machine room. The floor’s system has a death load of 50 kg/m^2 (Irving’s grid with a plate).

Table 1. Mexican load combinations

Service Combinations	Design combinations
D + Lm	1.4 D + 1.4 Lm
D + La + (Wx or Wy)	1.1 D + 1.1 La + 1.1 (Wx ó Wy)
0.9D + 0.9La + Ex + 0.3 Ey	1.1 D + 1.1 La + 1.1 Sx + 0.33 Sy
0.9D + 0.9La + Ey + 0.3 Ex	1.1 D + 1.1 La + 1.1 Sy + 0.33 Sx

Table 2. Resume of gravitational loads

Machines Room	Tower roof
Self-Weigh (Included in Program)	Self-Weigh (Included in Program)
Equipment: 2 Tn/Effective Area	-----
Floor system: 50 kg/m^2	Floor system: 50 kg/m^2
Maximum Live Load= 100 kg/m^2	Maximum Live Load= 40 kg/m^2
Accidental Live Load = 70 kg/m^2	Accidental Live Load = 20 kg/m^2

The maximum live load will have a value of 100 kg/m^2 in machines room and 40 kg/m^2 in the tower's roof [19].The accidental live load will be of 70 kg/m^2 in machines room and 20 kg/m^2 in tower's roof [19]. In machines room the loads are chosen for a plane roof because it will have people only in its maintenance. In the top of the tower, the loads are from a roof with a slope bigger than 5%.

The wind forces will be obtained from the Civil Works Design Manual of the Federal Electricity Commission of Mexico [20]. The structures will be considered in Group B with a wind Type 1. The local considerations will be taken from the Queretaro's City. In the close areas of machine room, the dynamic design pressure will be of 260 kg/m2. In all the other elements in the tower the dynamic design pressure will be of 155 kg/m2.

A resume of gravitational loads can be appreciated in Table 2.

All the loads and characteristics shown in chapter four will be used in the mathematical models created in the commercial program Sap 2000 V16.

5. RESULTS

5.1 Topology A

The topology chosen for one of the tower's mathematical models is the same as the experimental tower in Sonora (Shown in Fig. 5).

This topology has the necessary free spaces for the equipment hoisting and for their foundation in the floor. The energy receptors can be installed in all its faces to capture the solar energy in four directions. The structure is conformed in lateral restricted frames. The columns in the frames has a flexo-compression behavior, the beams have a flexional behavior and the braces has only axial forces.

The columns and beams lengths are of 6 meters. The braces have 6.7 meters of length. With these dimensions, the tower's members will need big transportation or the need of dividing the pieces in small ones (meaning more connections and factory work). For the lifting elements the need of a crane is not optional.

The topology is modular having constant sections and dimensions in all its height. This one is easy to be programed and optimized. The inner free space is the biggest in relation of the total area.

The sections used for this model are shown in Topology B.

The tower has a hexagonal shape in its base, helping it to capture in a more efficient way the solar energy. Because of the capturing is made Table 3.

The element's self-weight of the tower has a total value of 15.79 Tn. The high lateral displacement in the top of the tower caused by the wind forces has a value of 5.25 cms.

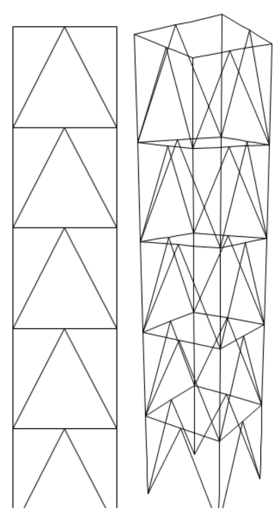

Fig. 5. Structural shape of experimental tower in Sonora

Table 3. Elements and characteristics of Topology A

Section	Element	Material	Weight [Tn]
HSS 4"x8"x1/4"	Beams	A500 Gr B HSS	3.4945
HSS 5"x5" 1/4"	Diagonals	A500 Gr B HSS	6.455
HSS8"X8"X5/16"	Columns	A500 Gr B HSS	5.84

5.2 Topology B

The tower has a hexagonal shape in its base, helping it to capture in a more efficient way the solar energy. Because of the capturing is made in six directions, in more directions with solar beams perpendicular to the tower's faces. Other polynomial shapes were used, but the topologies with higher number of sides had bigger self-weight than hexagonal one.

The structural shape is configured as a double spatial grid with hexagonal base. The side of the mesh has one meter and the separation between meshes has one meter too. The structure of the tower is shown in
Fig. **6**.

The kind of transport to be used in this topology will be cheap and easy because the shorter size of the elements (1 meter). Also, for the size of its elements, the connections will be easy to do for non-specialized workers. The transportation of modules besides individual elements is also easy because their shorter dimensions. The use of cranes is not indispensable.

This topology is easy to make in an algorithm and it is modular. The tower has a small group of different elements. Hence, there is no need of using an optimization algorithm. The free spaces are narrower than the other topologies. Because the double mesh has 2 meters in the diameter space, the total free space is less than the area with a complete free diameter.

The self-weight of the tower has 11.88 Tn and the maximum displacement in the tower's top is 5.14 cms caused by the wind forces. The weights and sections are shown in Table 4.

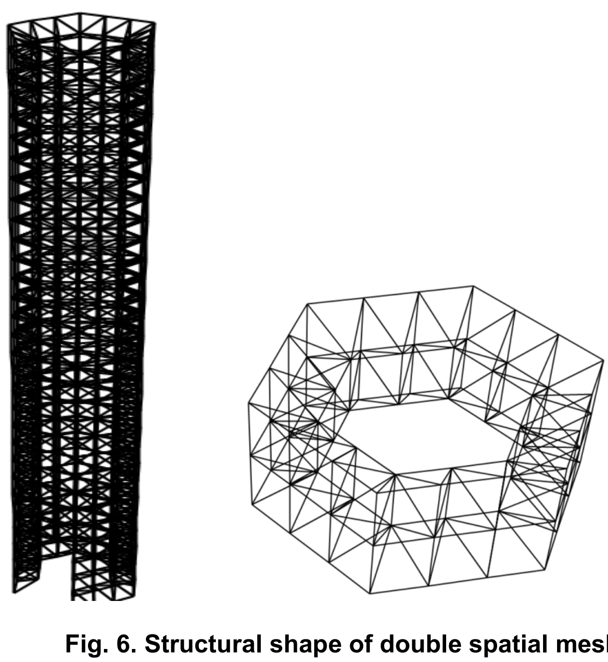

Fig. 6. Structural shape of double spatial mesh

Table 4. Sections and characteristic of Topology B

Section	Localization	Material	Weight [Tn]
PTR 2"x2" Cal 14	Other modules	A500 Gr A	11.1755
PTR 2.5"x2.5" Cal 7	1st, 2nd module	A500 Gr A	0.7077

5.3 Topology C

The structure is made by modules of lateral restricted steel frames. The restriction is formed by diagonal braces. The first modules have secondary elements supporting the principal braces. The frames formed squares of 3 x 3 mts. The longest elements are the diagonal braces with 3.35 meters. All these measures help that the transport of their elements will be practical and easy. The kind of connections to be used are easy and don't need specialized workers. Almost all the connections can be made in factory. The structural shape is shown in
Fig. **7**.

The structure in its modular shape is able to be used in an algorithm and easy of being optimized. This topology has different groups of elements that allow the use of an optimizing algorithm. This shape helps the use of its inner area for the needs of being a heliostat tower (equipment and stairs).

In topologies B and C, the hexagonal shape helps that solar energy can be captured with more efficiency. Because the minimization of the refraction of light in their six faces in compare with the four sides tower. The sections and weight of topology C is shown in Table 5. The total weight of this topology is 10.25 Tn. The maximum displacement has a value of 5.53 cms.

6. DISCUSSION

The analysis of the three topologies is summarized and shown in Table 6.

Table 5. Sections y characteristics of topology 3

Section	Element	Material	Weight [Tn]
HSS 6"x4"x3/16"	Beams	A500 Gr B HSS	3.2903
HSS 6"x6"x3/16"	Columns	A500 Gr B HSS	3.9735
PTR 2"x2" Cal 11	Diagonals	A500 GrA PTR	0.2567
PTR 3" Cal 11	Secondary Braces	A500 GrA PTR	2.7288

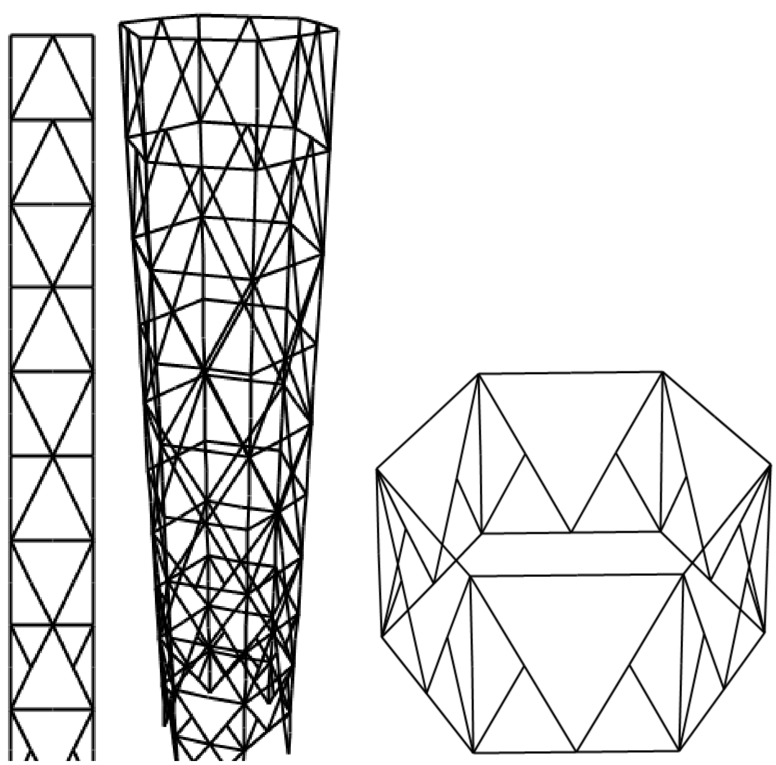

Fig. 7. Structural shape of tower with lateral restricted frames

Table 6. Resume of topologies' characteristics

Structural topology	A	B	C
Self-weight [Tn]	15.79	11.88	10.25
Max Disp. [cms]	5.25	5.14	5.53
Max. length [mts]	6.7	1	3.35
Use of cranes	Yes	No	Yes
Quantity of different connections	Low	High	Middle
Receptor's faces	4	6	6
Capacity of being optimizable	Middle	Low	High
% Area of free space in a square of 6mts x 6mts	100%	43%	65%
Quantity of elements	80	3849	360

The topology with less weight is the structural shape C. The weight will be a primary factor in the comparison between the topologies. The stiffness shown through the displacements in the tower is bigger in topology B. Although, the difference between the three topologies is less than a half centimeter. The three options have displacements shorter than the Mexican standards allow.

The members of topologies B and C are easy to be transported because of their lengths. The shapes A and C requires cranes in their construction. This analysis is inversely proportional to the connections number (Topology B has de biggest number of them).

For their hexagonal shape, the topologies B and C are more efficient in the reception of solar energy than topology A. The C one has more characteristics and more combinations of different members that becomes the best to be optimized. The free spaces of topology A are bigger than B and C ones. Also, the topology with the smallest quantity of members between these three is the topology A.

7. CONCLUSIONS

It can be concluded of the last analysis, that the topology B and C have the same number of characteristics as the best topology (with four each one). The topology A has three dominant characteristics. There is a draw between the topology B and C. Analyzing the factors where topology A is the best, the structural shape C is better than B.

The total self-weight of the tower and the capacity of being programmable are considered as a high impact factor. For this consideration and the best behavior of the structural shape in the characteristics that topology A is better, the conclusion of this work ends with the election of model C as the best topology to be used in the optimization of a central tower in a heliostat field.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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