

Design of Lattice Wind Turbine Towers With Structural Optimization

Pedro Américo Almeida Magalhães Júnior, Igor Guasti Rios, Tiago Simão Ferreira, Aniceto Carlos De Andrade Júnior, Osvaldo Abadia De Carvalho Filho and Pedro Henrique Deogene Soares

Departamento de Engenharia Mecânica, Pontifícia Universidade Católica de Minas Gerais, Av. Dom Jose Gaspar, 500 - Coração Eucarístico, CEP 30535-901, Belo Horizonte, M.G., Brasil (paamj@oi.com.br, +55 31 99513121)

ABSTRACT

This article aims to study the self-supporting truss towers used to support large wind turbines in areas with high altitude. The goal is to evaluate and validate numerically by finite element method the structural analysis when the lattice structures of the towers of wind turbines are subjected to static loads and these from common usage. With this, it is expected minimize the cost of transportation and installation of the tower and maximize the generation of electricity, respecting technical standards and restrictions of structural integrity and safety, making vibration analysis and the required static and dynamic loads, thereby preventing failures by fractures or mechanical fatigue. Practical examples of towers will be designed by the system and will be tested in structural simulation programs using the Finite Element Method. This analysis is done on the entire region coupling action of the turbine, with variable sensitivity to vibration levels. The results obtained for freestanding lattice tower are compared with the information of a tubular one designed to support the generator with the same characteristics. At the end of this work it was possible to observe the feasibility of using lattice towers that proved better as its structural performance but with caveats about its dynamic performance since the appearance of several other modes natural frequency thus reducing the intervals between them in low frequency and theoretically increase the risk of resonance.

Keywords: Structural Analysis, Vibration Analysis, Self-Supporting Truss Towers, Wind Energy, Finite Element Method, Structural Optimization.

I. INTRODUCTION

The Wind energy is a renewable energy that can be used directly or be transformed to other types of energy, such as electricity. The first time known of the use of wind energy dates to the year 3000 BC with the first Egyptians sailboats. A few millennia later (s. VII in Persia) arose the first windmills that would grind grain or pump water. Nowadays, it can be produced with high electrical efficiency, and are called wind turbines. A wind turbine is formed by a set of blades (usually three) connected to a rotor through a gear system, connected to an electrical generator. All this machinery (wind turbine) is placed on the top of a mast or tower where they are more affected by the wind. The length of the blades define the diameter of the area swept by the same and the larger this area is, the greater the power that can generate a wind turbine. You can find everything from small wind turbines of 400 W and approximately 1m in diameter paddle or huge wind turbines of large wind farms of 2,500 KW and 80 m diameter blades.

For small household or agricultural plants the most useful and workable turbines are those with a

sweeping diameter of 1 to 5 m, that can generate from 400 W to 3.2 kW. These have an advantage, moreover, that may start at a wind speed lower than the larger, such as sea breezes or Mountain Winds, and produce the most amount of energy. They need a minimum wind speed of 11 km/h to boot (compared to 19 km/h of the biggest), achieve their maximum efficiency at 45 km/h and be stopped with winds over 100 km/h to avoid engine damage or wear or overload.

Here we intend to study the towers of wind turbines from the preliminary analysis of the velocity profile (turbulent) wind up with about 50m tower base in mountainous regions. Note that the wind speed and turbulence intensity are conditions that dictate the standards of design loads of the towers and wind turbines.

From the study

f aero-elastic structure (blades / turbine + tower), can be detected excessive vibration levels, which in addition to jeopardizing the proper functioning of the system, in extreme cases lead to their ruin. An alternative to this problem is the installation of

passive control devices. A passive control system is summarized for the installation of one or more devices incorporated into the structure which absorb or consume a portion of energy transmitted by dynamic loading, thus reducing dissipation of the energy in the members of the main frame. One of the most common control devices is the tuned mass damper (AMS), which in its simplest form, consists of a mass-spring-damper, it acts by transferring part of the vibrational energy to the structure itself. The use of AMS coupled to the turbine to reduce vibrations caused by wind are already being studied, but remain to be detailed aspects such as the robustness of the AMS in relation to changes in the parameters of the system as a whole. The addition of these buffers changes the dynamic analysis of the system requiring a reassessment of the whole blade / turbine + tower. This modification generates a

significant change in the dynamic analysis or of the structure inducing feedback phases of interaction fluid-elastic and aero elastic optimization. Eventually, this new configuration will generate the need for further studies on the mechanical and structural reliability.

Figure 01 details the best region in the Brazil, where one can see the great wind potential. It is observed that the higher the wind speed, the greater the amount of power generated by wind turbines. The minimum thresholds of attractiveness for investments in wind power depend on the economic and institutional contexts of each country, varying in terms of annual average speeds between 5.5 m/s and 7.0 m/s (19.8 km/h and 25,2 km/h). Technically, annual averages from 6.0 m/s (21.6 km/h) already provide favourable conditions for the operation of wind farms [1].

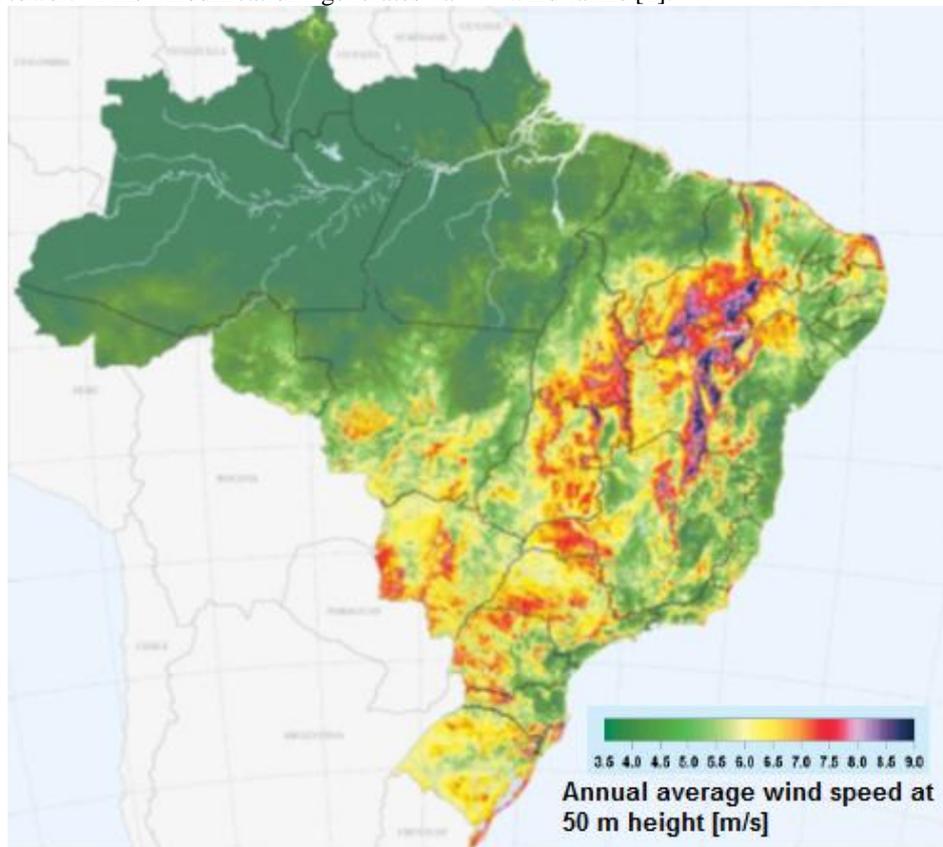


Figure 01: Wind Atlas of Brazil, with some areas selected as most promising ventures of wind farms [1].

Figure 02 shows the annual predominance of wind direction, varying according to the size of the arrows. Regions with lower change of direction are

more favorable for the implementation of wind farms. In these places, aero generators receive winds, considered useful, in a long time during the year.

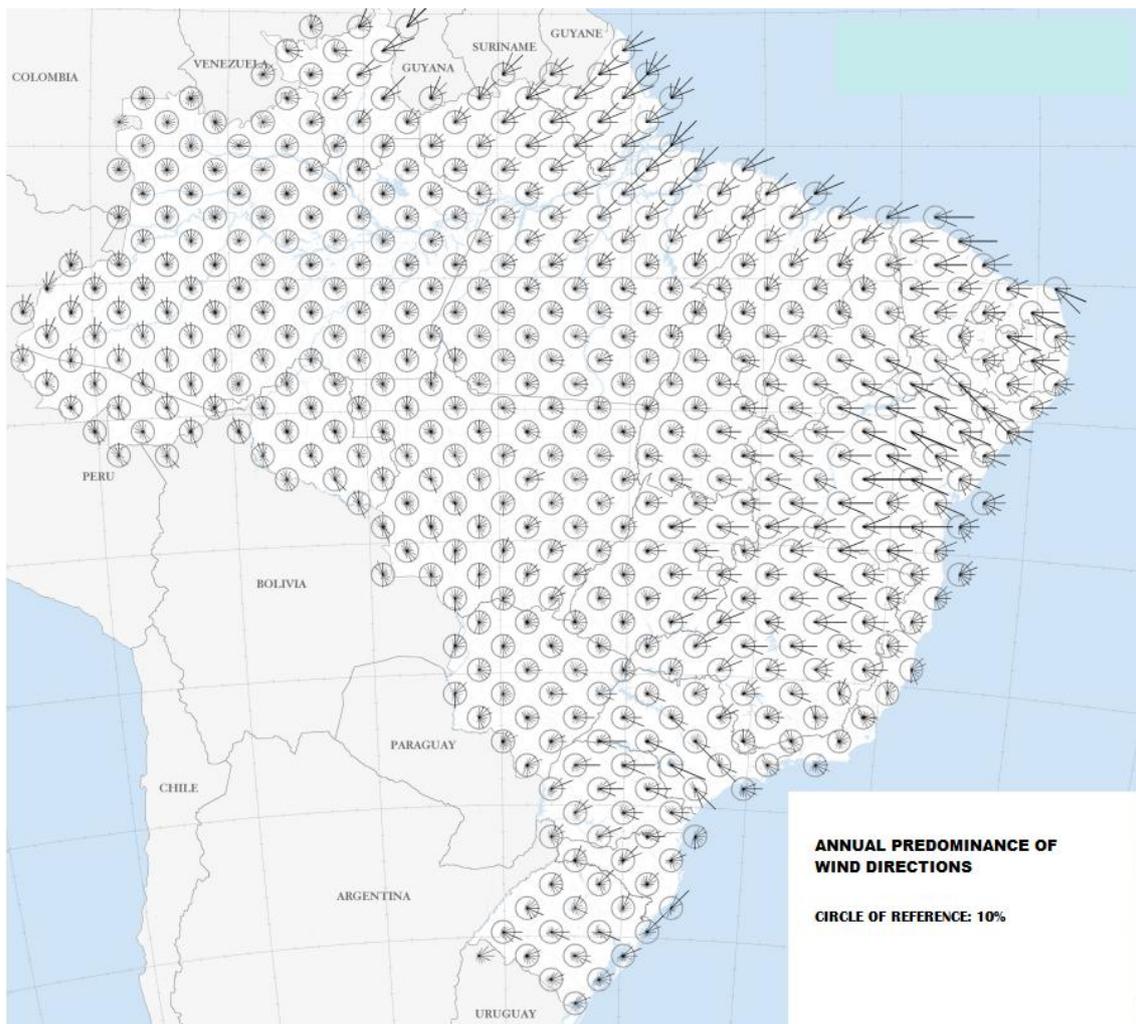


Figure 02: Wind Atlas of Brazil, areas with annual predominance of wind directions [1].

II. DESCRIPTION OF THE MODEL IN FINITE ELEMENT

The wind tower lattice steel studied in this article refers to the model to a tower model standard for energy transportation in Brazil, the results of this model will be confronted with tubular tower model. This tubular tower is present in several countries like Spain, Portugal and Germany having a capacity to generate 2 MW of electricity. The model has a shape of a truncated hollow cone divided into three parts in order to facilitate transport and assembly. The first has a height of 21.77 m and base diameter of 4.30m, the second has a height of 26.62 m and base diameter of 3.91m on top. Finally, the third part has a height of 27.81 m in diameter at the base of 3.45 on op. It becomes to a total height of 76.20 m.

The self-supporting lattice tower used in this study is the initial reference used by towers in Brazil strengthened as wind towers truss designed in some countries, highlighting Germany.

The model lattice has a shape of square profile divided into two parts in order to increase its bending stiffness and torsion. The first has a height of 48.0 m and a square profile with base edge on the basis of 24.0 m, the second at a height of 28.12 m based on 8.00 m finishing edge on top of the second part with a square profile edge of 6.00. Figure 03 illustrates the divisions of the lattice tower. The lattice tower comprising the feature profile at "L" with dimensions of 44.45 mm x 44.45 mm and a thickness varying according to the voltage levels on the results obtained charging pro sustained action of the wind.

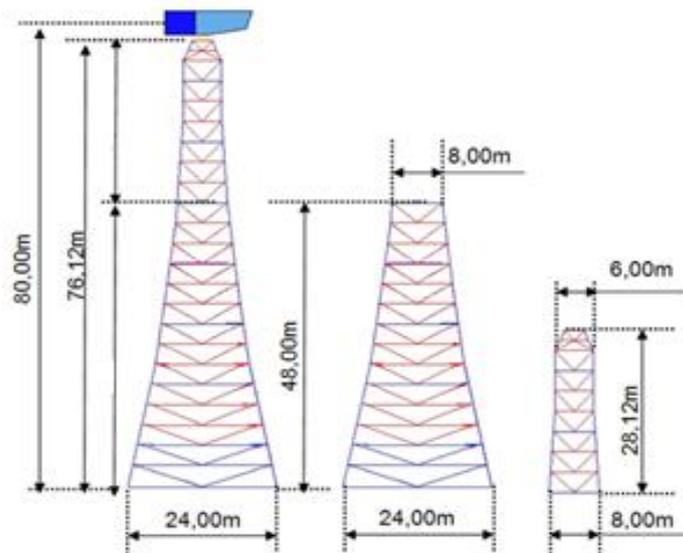


Figure 03:Representation of the lattice wind tower.

Until the final construction of the tower used in this work more than 40 profiles were created and tested until its final outcome was considered relevant as its viability structure.

In Figure 04, we can observe advancement of the project from its conception to the final model of the tower.

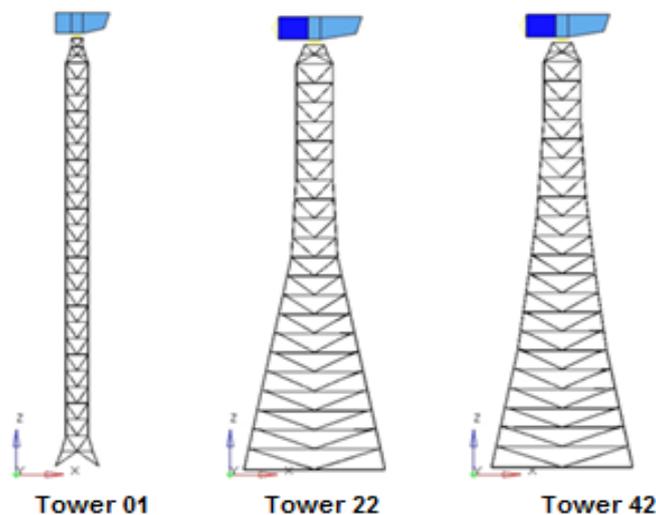


Figure 04:Advancement Project freestanding lattice tower wind.

Simplifying assumptions:

- Aiming to computational implementation of a mathematical model, through the use of finite element method in order to translate more realistically the effect of wind tower studied in the article were based on the following

Simplifying assumptions:

- It is the only system of linear material.
- It is considered that binding of parts of the tower does not suffer the effect of rotation, using joints simplified in drive bezel.

- The nacelle and rotor and propeller been simplified calibrated with a material having a density which is its total weight.
- The tower had its base simplified considering the rocky terrain of the study area. In this case a collet were considered rigid base of the tower preventing any rotation and translation on the base.

III. RESULTS FOR STATIC AND DYNAMIC ANALYSIS

As mentioned, this article presents the results in linear static and dynamic analysis. Static analysis

aimed to evaluate the consistency of the model in terms of a preliminary analysis and only to confirm the structural viability of the tower. The dynamic analysis, focus of this dissertation, contributed to the calibration of the model by comparing the fundamental frequency, achieved numerically, with numerical values obtained from other studies correlated and validated experimentally.

3.1 Description of the comparative linear static analysis

The nonlinear analysis was performed from the application of displacement in the centre of the

rotortower toward the x axis (wind at 0° project), in the direction of the x axis. Figure 05 illustrates the nacelle positions adopted in this thesis for the application load. This is justified because the nacelle tower has the same effect in any wind direction for a lattice tower. Analyses were performed with a charge equivalent to that used in the work offset reference for comparison. Figure 05 shows the comparison between the two towers in position for comparison.

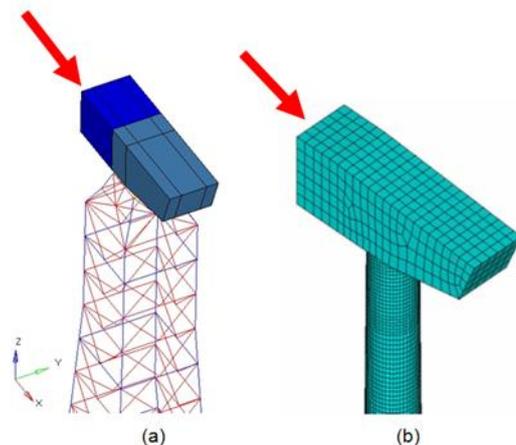


Figure 05: Advancement Project freestanding lattice tower wind.

3.2 Force applied as a load in the direction of the axis x - 0° wind

Figure 06 shows a graph of load acting on the rotor hub of the tower versus the displacement at the point of application of the load simulating the transmission of the action of the wind on the blades

to the wind turbine at position 0°. The chart below shows the behaviour of the towers represented by Figure 4 (a) conducted in this work with a load of 1800KN and compared with results obtained from reference figure 4 (b), these generated an offset prescribed.

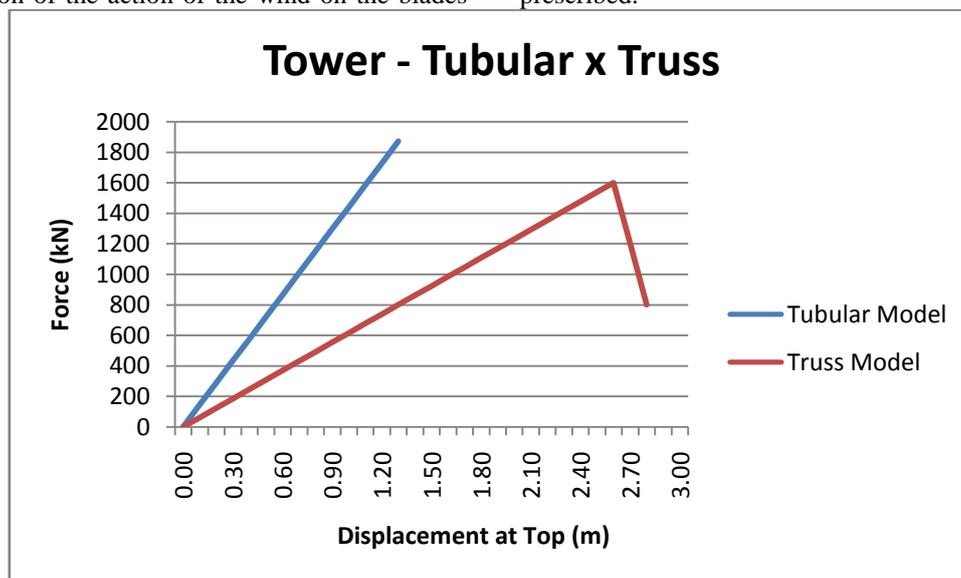


Figure 06: Load versus displacement curve for the wind to 0°.

3.3 Dynamic Analysis

Will present the results obtained by computational modelling of the structural model in study for analysis of eigenvalues (natural frequencies) and eigenvectors (mode shapes). Afterwards, it proceeds to a harmonic analysis, aiming to identify the frequencies of the model with the greatest participation in the dynamic response.

Table 1: Presents the results obtained for the lattice tower used as a study in this thesis and compared with the simulation results of the tubular tower above.

Fundamental frequency: Comparative Analysis.

Frequency	Numerical Analysis (Hz) lattice tower	Numerical Analysis (Hz) Tubular tower	Δ (%)
f01	0,29	0,36	19,4
f02	0,30	0,36	16,6
f03	0,39	2,59	84,9
f04	1,06	2,64	54,8

In Table 1 it can be seen that the results provided by the numerical model are very close, but below the tubular tower model, with differences already expected under the numerical point of view. With these results we can see that the lattice tower

responds more flexibly and features a large numbers concentrated in low-frequency modes. The comparative results between the two towers, lattice and tubular, are present in Figure 7 to Figure 10.

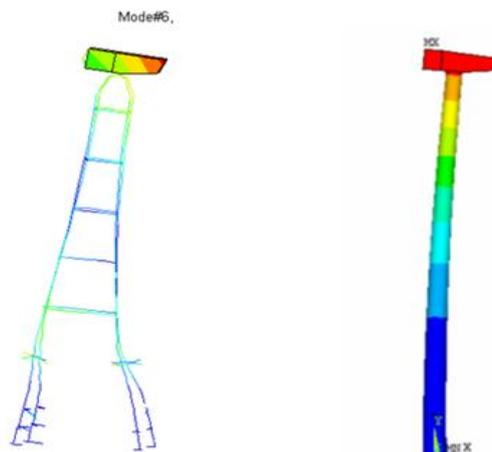


Figure 7: Vibration mode corresponding to the first natural frequency of the structural model: bending in the XY plane.

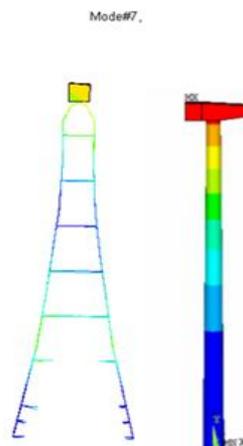


Figure 8: Vibration mode corresponding to the second natural frequency of the structural model: bending in the YZ plane

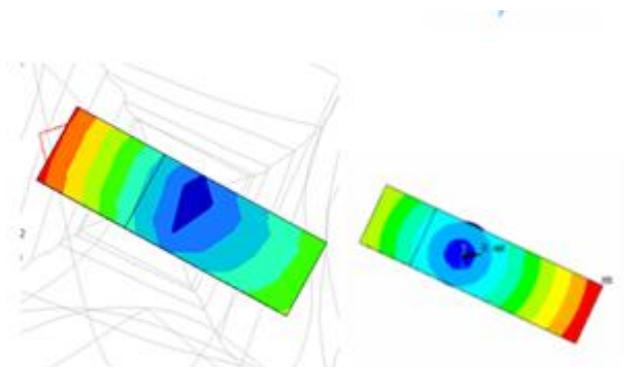


Figure 9:Vibration mode corresponding to the third natural frequency of the structural model: twist

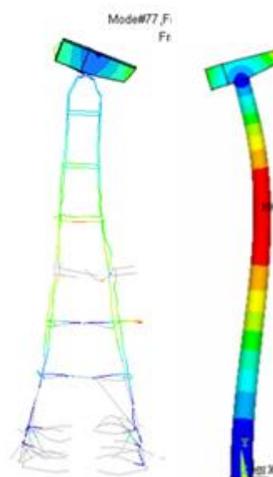


Figure 10:Vibration mode corresponding to the fourth natural frequency of the structural model: bending in the XY plane

Figure 7 to Figure 10 are illustrated the first four vibration modes of the structural model comparing lattice tower with tubular tower model reference work. Figure 7 shows the first natural frequency with a value equal to 0.29 Hz ($F01 = 0.29$ Hz) associated with a flexure in the XY plane. Figure 8 represents the second natural frequency with a value equal to 0.30 Hz ($f02 = 0.30$ Hz), associated with the first bending mode in the YZ plane. In Figure 9 the third vibration mode is displayed with a value equal to the natural frequency of 0.39 Hz ($f03 = 0.39$ Hz), associated with the first torsional mode. The fourth natural frequency illustrated in Figure 10 has a value of 1.06 Hz ($f04 = 1.06$ Hz) and is associated with the second mode of bending towards the axis XY.

IV. STRUCTURAL OPTIMIZATION

In order to decrease the time needed to prepare structural truss that meets the requirements of shipping cost, construction and installation, we propose a model for generating self-supporting tower

lattice for wind turbines, with computational assistance given some input parameters generates and optimizes the structural design of the towers and foundations based on the internal forces. [19]Classifies the structural optimization of tower lattice into sub-problems of size, shape and topology, as in [20,9,23], having in some cases tools to aid problem solving multi-objective [10].

Topological design variables determine an initial structural layout whereas shape and sizing parameters give the shape and dimensions of structures respectively. The optimum shape and sizes of the structure are then found in the later design stage. This is often called multi-stage optimisation. Nevertheless, it has been found that the better design process is to perform topology, shape, and sizing optimisation simultaneously [20].

In the field of structural optimization of tower lattice, various methods have been proposed using Ant Colony Optimization [15], Artificial Bee Colony [14], Particle Swarm Optimizer [11] and others using

Genetic Algorithm [12]. Genetic Algorithm (GA) was proposed by [18], based on natural selection by Charles Darwin. With that in GA, an individual is a data structure that represents one of the possible solutions to the problem. Individuals are then subjected to an evolutionary process that involves reproduction, sexual recombination (crossover) and mutation. After several cycles of evolution, the population will contain individuals more able [21], the best solution found in relation to population initially generated. GA has the advantage, the

flexibility to adapt to find solutions to the proposed problem without a knowledge derived from problem to deal with, and presenting to the end of the run not only one solution, but several solutions of the problem analyzed. [22] Presented a solution to minimize the mass in truss up to 940 bars, proving the efficiency of the use of GA in solving this kind of problems. Figure 10 is a schematic illustration structural optimization multidisciplinary tower lattice.

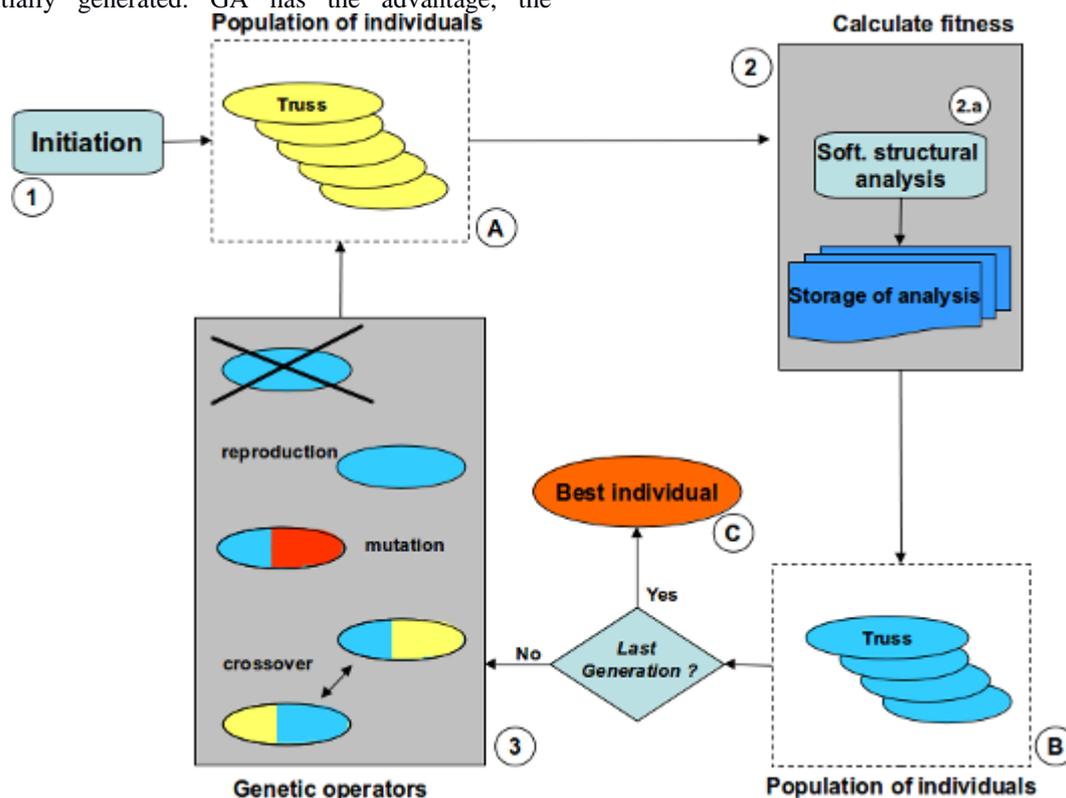


Figure 11: Scheme for structural optimization multidisciplinary of tower lattices.

Step 1 - some parameters are reported to the GA for the generation of the initial population of individuals, such as population size, rate of elitism, mutation, and the characteristics related to the location of the truss, and its structural characteristics such as height and size of the truss, maximum cost allowed for the construction, wind speed in the region of the tower installation. - *Step 2* - runs the method of structural analysis. - *Step 2a* - for each individual generated, analysis will be performed to check how near to the ideal structure of the truss is, taking into account the parameters reported initially and in the media that new structural processes are being generated, they are stored in the database for future structural analyzes generated. In B for each one, the GA returns the fitness value. After checking the suitability of individuals in the population, an inquiry is made whether there all generations of the population initially generated A, were evolved. If so C, the best

individual, the one with the highest fitness value, is selected, the truss is generated with the structural data present in the best element selected. - *Step 3* - run operations intersection, reproduction, mutation and deletion of individuals so that it formed a new population.

4.1 Truss optimization

The main objectives for the optimization of the lattice is, to minimize the weight of the tower, reduce their manufacturing cost and provide greater ease of construction.

The cost of production must take into account several factors such as transportation, installation, construction and installation of the tower. The more complete and detailed is the analysis of costs, the lower the cost for the implementation of wind farms. The cost calculation is basically due to the following factors:

1. Number of bars (N_m): the points to note are the material of the bars, its painting, transportation and work in the extremities (holes and welds):

$$C_m = \sum_{i=1}^{N_m} K_m + K_{mm} \rho A_i L_i \quad (1)$$

Where K_{mm} is the cost of steel (\$/ton), ρ is the unit weight of steel (ton/m²), A_i and L_i are the cross-sectional area and length of the member. K_m is the cost to cut, paint and prepare the bars.

2. Number of nodes (N_n): In this case it is considered the material in the connections, welds, nuts and bolts, assembly and installation:

$$C_n = \sum_{i=1}^{N_n} K_n + j_i h d t f \quad (2)$$

Where K_n is the material and installation cost per bolt, N_n is the total number of bolts, h , d and t are the dimensions of the footings, and f is the cost of material (reinforcing steel and concrete) for the footings (\$/m³). The j_i are number of footings per bolt.

3. Number of supports or bases (N_b): Takes into account the construction of foundations for the tower:

$$C_b = K_b N_b \quad (3)$$

Where K_b is the unit cost per tower foundation.

4. Number of types of cross sections of the bars (N_t): In this case, the point to note is the operational cost of tower assembly. Most manufacturers stipulate these values:

$$C_t = K_t N_t \quad (4)$$

Where K_t is the estimated cost to use a specific profile of a manufacturer.

5. Number of bars arriving at a node (N_{nm}): It takes into account the complexity of setting up a node. In this case, the more bars that are connected to a node, the more expensive the process becomes.

$$C_{nm} = \sum_{i=1}^{N_n} K_{nm} N_{nm} \quad (5)$$

Where K_{nm} is the cost to build a bar in a tower node.

6. Tilt angle of the bars that come on a node (θ_{nm}): It is considered the ease of installation, construction and maintenance of the angle between the bars:

$$C_\theta = K_\theta \sum_{i=1}^{N_n} \sum_{j=1}^{N_{nm}} \sqrt{[\theta_{ij}(90 - \theta_{ij})(180 - \theta_{ij})]^2} \quad (6)$$

Where K_θ is the cost of installing bars with an angle and θ_{ij} is the smallest angle between two bars joined at a node.

These values should be subject to the requirements:

$$\begin{aligned} \sigma_{i\min} &\leq \sigma_j \leq \sigma_{i\max}, i=1..N_m, j=1..l_c \\ -\sigma_i &\leq -\sigma_i^E, i=1..N_m \\ \delta_j &\leq \delta_{i\max}, i=1..N_n, j=1..d_c \\ \omega_m &\leq \omega_m^*, \text{ for some natural frequencies } m \\ \omega_n &\geq \omega_n^*, \text{ for some natural frequencies } n \\ 0 &\leq A_j, j=1..N_l, \text{ for some sections of the manufacturers} \end{aligned} \quad (7)$$

Where N_m and N_n are the number of members and nodes of the ground structure, respectively; A_j are cross-sectional area of the j th member; d_c and l_c are the number of displacement constraints and loading conditions, respectively; σ_{ij} is the stress of the i th member under j th loading condition and $\sigma_{i\min}$ and $\sigma_{i\max}$ are its lower and upper bounds, respectively; δ_{ij} is the displacement of the i th degree of freedom under the j th loading condition, $\delta_{i\max}$ are the corresponding upper limits; σ_i^E is the stress at which the i th member buckles, i.e. Euler buckling stress; ω_m is the m th natural frequency of the structure and ω_m^* is its upper bound. ω_n is the n th natural frequency of the structure and ω_n^* is its lower bound.

The Euler buckling stress of the i th member is calculated as:

$$\sigma_i^E = \frac{-\kappa_i A_i E}{L_i^2} \quad (8)$$

Where E is the modulus of elasticity and κ_i is a constant which is determined regarding the shape of the section.

Adding all these factors, we obtain the total cost of work (C).

$$C = C_m + C_n + C_b + C_t + C_{nm} + C_\theta \quad (9)$$

To minimize the weight of a lattice tower for wind turbines, the structure must follow limits and minimum tension characteristics, flexibility and buckling. However, there are several loads acting that should be considered as the weight of the wind turbine, the force of the wind and the torque of the spades.

In this study, at first a small structure was done, manually made (Figure 12). After that, the optimum structure was generated in Optistruct by the method of finite elements. In this procedure was also employed a considerable increase of the height of the structure so that it can be used in large turbines. As new structures were made, its weight and construction cost were reduced, as in figure 13 and 14.

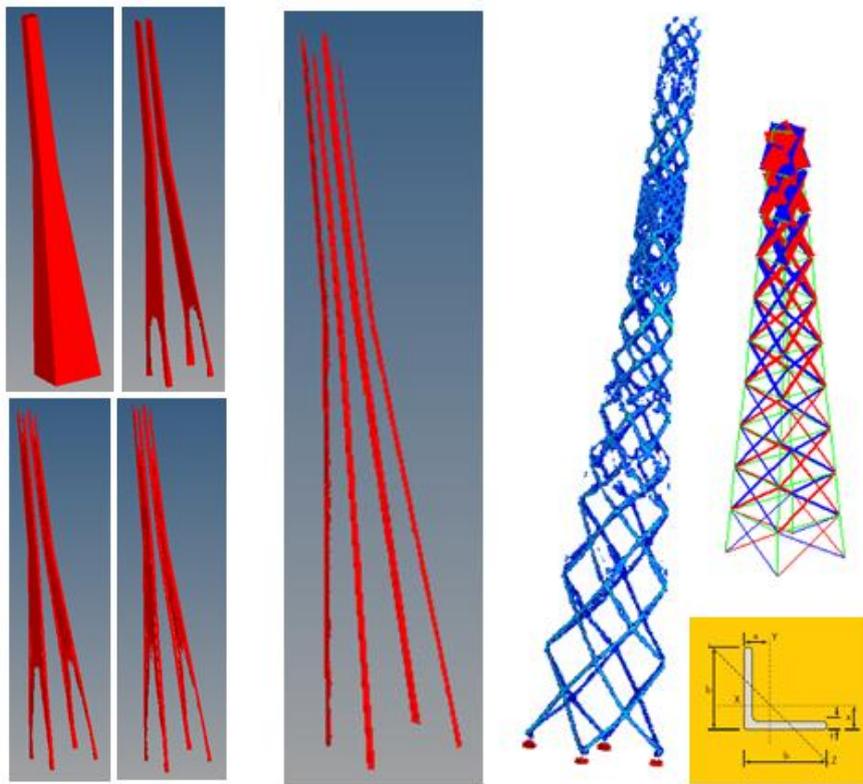


Figure 12: Steps in the optimization process in Optistruct ®. In yellow, the profile of bars used.

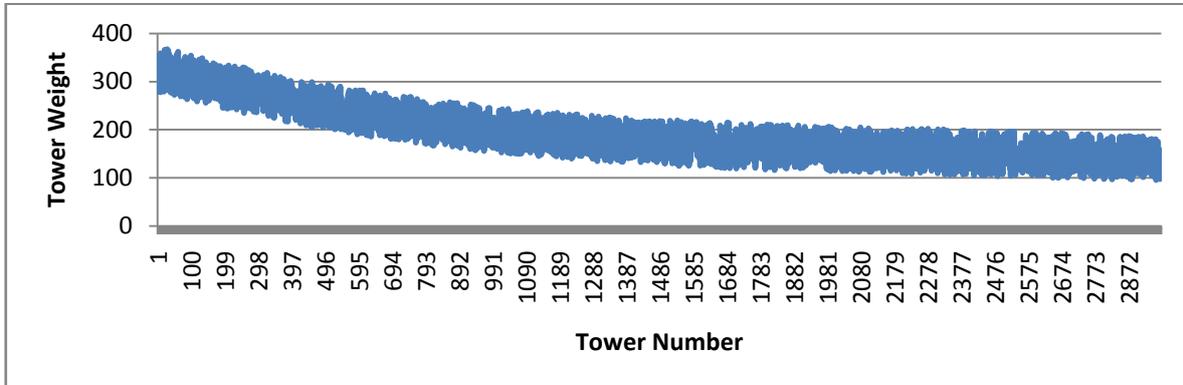


Figure 13: Relation between the weight of the tower and his number

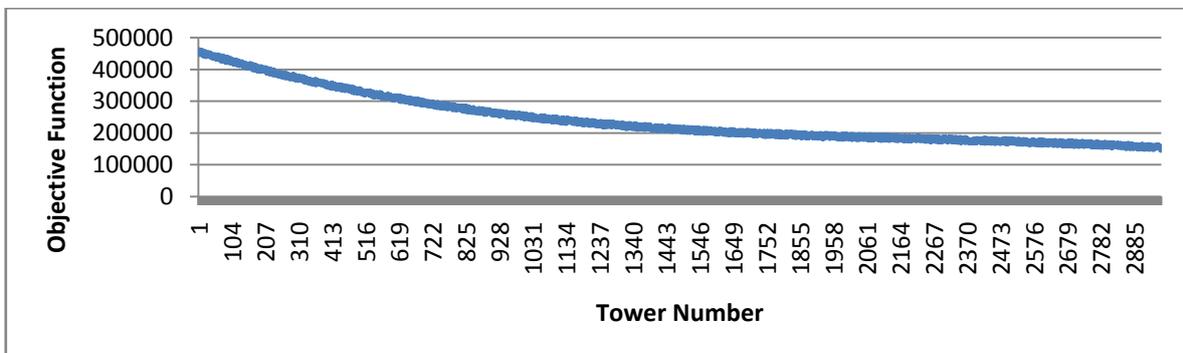


Figure 14: Relation between the price of the tower and his number

4.2 Results

Made the processes presented above, the best structure was named as T3003. The tower showed the best relationship between production price and mechanical requirements. Its features are: 122.80 m height, 18.31 m wide base, volume of 12.09 m³, total weight of 94885.03 kg, 417 nodes and 1164 bars.

The analysis of buckling, deformation and tension were calculated using the programs ANSYS® and SAP2000®. The forces were applied on top of the tower:

- Weight of turbine $F_z = -1.067.000$ N
- Force of the wind $F_x = F_y = 423.373,1152$ N
- Torque of the blades $M_y = M_x = 1.176.915,5977$ N

The results were a maximum deformation of 2.4226 m at the top of the structure, maximum buckling of 0.72263 m located in the midline of the tower, maximum tension in the bars of $4,8537.10^6$ N and minimum of $-5,4803.10^6$ N.

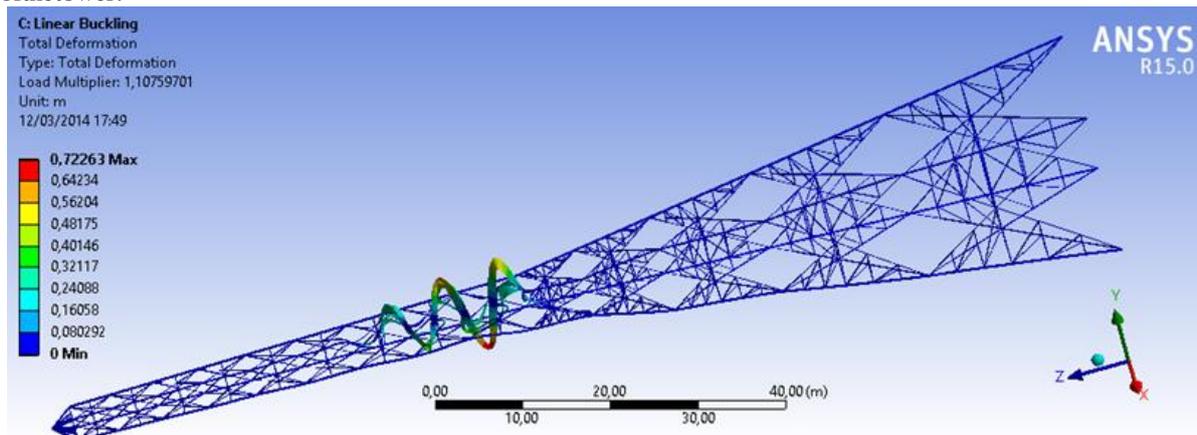


Figure 15: Buckling of the tower due to applied loads in ANSYS®.

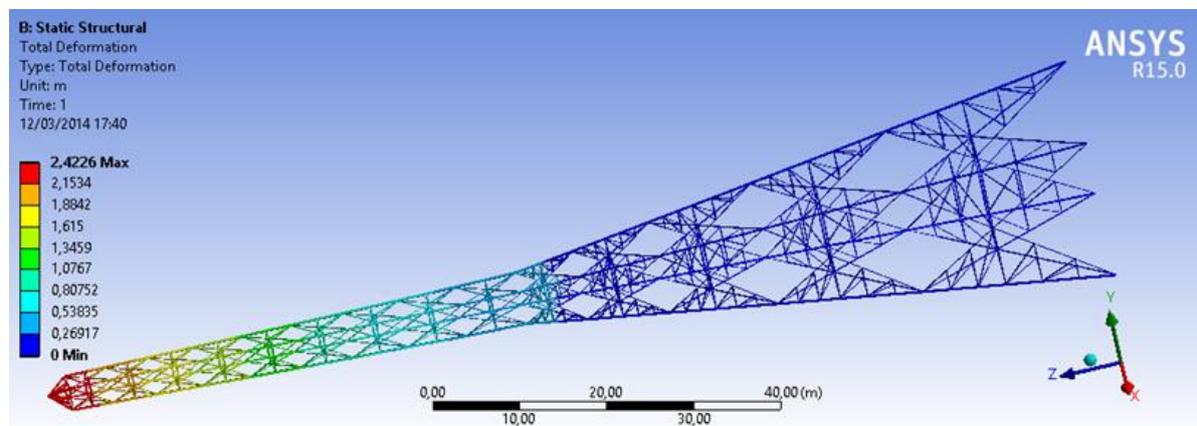


Figure 16: Total deflection due to loads in ANSYS®.

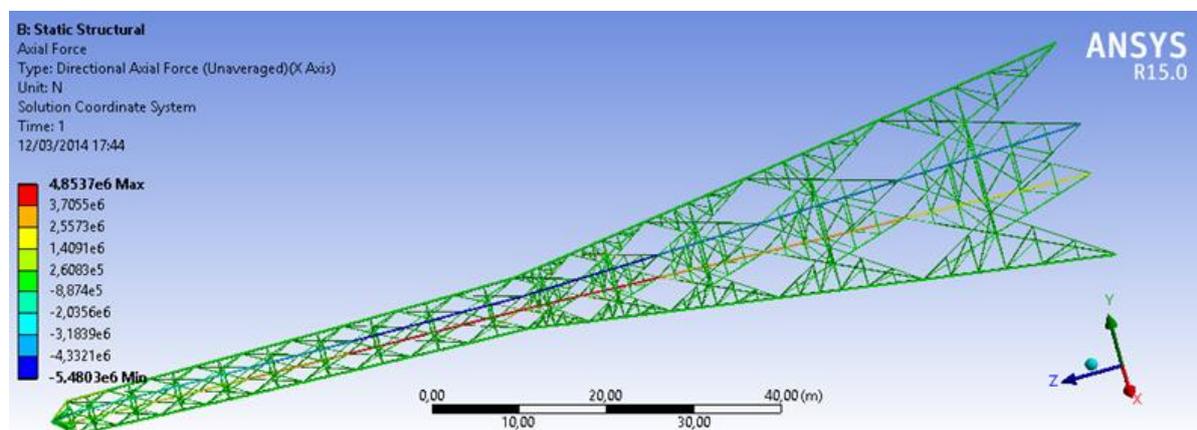


Figure 17: Axial forces in the bars due to applied forces in ANSYS®.

The characteristics of the best tower obtained, show the main bars with an inclination of around 80° to the ground and secondary bars forming angles of 30° with the four main side bars. These values are very close to those found in [24] for optimized trusses. In [24] these data are 80° and 29.9° respectively. These angles correspond to the best relationship between the height of the structure and the cost of production.

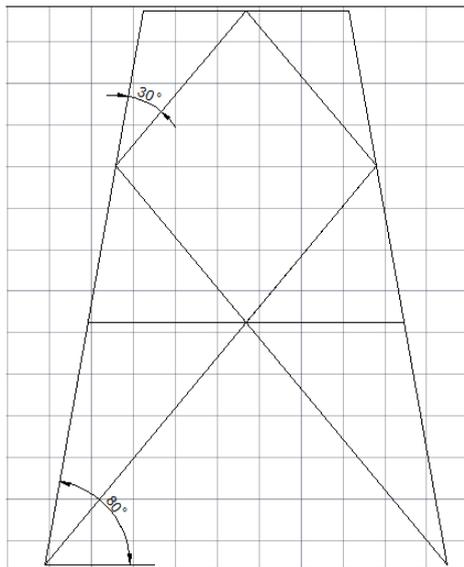


Figure 18: Angle position of the lattice tower.

V. CONCLUSIONS

This work aimed to study the static and dynamic analysis of a wind tower lattice according to the standards set by the energy sector. This assessment was carried out through the use of standard techniques discretization via finite element methods and also using other works as a means of validation.

The linear static and dynamic analyses were studied by applying loading to simulate the action of wind on the propeller blades Tower analysed.

This work is divided into two distinct phases. In a first step analyses were performed linear static analysis of the tower. The next step included the dynamic modelling for various kinds of analyses such as the modal response of the system. In both phases of this work, lattice tower was compared with the tubular towers that are already widely used for this purpose.

The results of the static and dynamic responses of wind towers model were presented in terms of displacement and maximum stresses acting on the towers.

For the two research fronts for validation of a self-supporting lattice tower wind, this was the first to validate the structure of the tower; this was done with some static analysis. The second was to validate the performance of this tower as its dynamic response.

The finite element numerical method proved to be quite useful and accurate in the process of assessing the structural analysis of the tower wind study. Its use was effective in predicting static and dynamic analysis, when compared with results obtained by other studies with the same focus.

It was also observed that no tower collapsed in any of the forty-two (42) models analysed. Buckling or yielding occurred only in some bars whose efforts were distributed to the adjacent bars.

To the front of this second search, the dynamic analysis, it was found that a self-supporting lattice tower responds modes at frequencies slightly lower when compared to tubular towers on average 8% lower. Another fact that calls too much attention on the results of dynamic analysis is the large number of modes having a lattice work tower, this may cause a higher risk of occurrence of resonance which can be a problem for lattice towers, and this is because the interval between frequencies is smaller than that of tubular towers. However, the risk may be avoided acting on changes such as the shape of the profile of trusses.

Soon, lattice towers are a good option as saving for wind turbine application. It is also an attractive alternative to tubular towers that have typically been used so far.

Other favourable point for lattice towers is the analysis taking into account the low voltages across all components and very safe margin for buckling.

The future of wind power seems to be the large wind turbines, with capacity from 1.5 to 20 Megawatt and blades with 50 meter radius. To support these large wind turbines, tall towers, with more than 100 meters are required. The higher the tower, the greater will be the wind speed and more power will be generated (proportional to the cube of the wind speed power). For these heights, tubular steel towers are very expensive.

To create lattice towers with low cost one should use the structural optimization to obtain structures with the least possible weight. But the structural optimization is not all; it should be taken into account the cost and ease of construction. This imposes restrictions on the symmetry on 4 sides, number of bars (not very large), number of profile sections of different size and techniques known to construct lattice towers. That is, the research seeks a tower of low cost, easy construction and installation and not just the use of process of topological optimization to design the towers.

Using structural analysis, it was observed that most of the loads are supported by the 4 side bars; this justifies the industry to launch a simple profile bracket "L" shaped with dimensions of 250mm to 300mm and thickness of 35mm (or size of 10 to 15 inches from the side and more than an inch thick).

These new profiles facilitate the construction and reduce cost.

For secondary barstowers, which has among other functions to solve the problem of buckling, the study revealed interesting profile brackets simple "L" with a very long length (greater than 130mm) and a thin thickness (less than 10mm). Something that the steel industry has also worked little. However, this is a good option.

Tall towers are ideal for the use of wind energy in Brazil, which have winds with moderate speed (6-10m/s), no hurricanes, tornadoes and earthquakes. It has vast areas of lowland mountains and plateaus. Besides it has a tropical and subtropical climate.

Central regions in Brazil, have areas with good wind incidence during the year with little variation in their direction. Moreover, these areas have lacking in the supply of electricity. This is a promising area for the deployment of wind turbines.

Wind energy is a complement to hydroelectricity, since hydroelectricity is favored with the presence of rain and wind is favored with dry climates.

REFERENCES

- [1] AMARANTE, O. A. C., et al, 2010, *Atlas do Potencial Eólico Brasileiro*, Ministério de Minas e Energia, Eletrobrás, CEPEL.
- [2] AMARANTE, O. A. C., SILVA, F. J. L., 2002, *Atlas Eólico do Rio Grande do Sul*, Secretaria de Energia Minas e Comunicações do Estado do Rio Grande do Sul. ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 6123: Forças devidas ao vento em edificações. Rio de Janeiro: ABNT, 1988
- [3] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 5422: *Projeto de linhas aéreas de transmissão de energia elétrica*. Rio de Janeiro: ABNT, 1985.
- [4] ENERCON, 2004, "E70 - Booklet", *Enercon International Department*, www.enercon.de acessado em 20 de junho de 2011.
- [5] FERREIRA, T.S., 2012, *Comportamento Estrutural de Torres Treliçadas Autoportantes de Aço para Suporte de Turbinas Eólicas*, Dissertação (Mestrado em engenharia mecânica) - Pontifícia universidade Católica, Programa de Pós-Graduação em Engenharia Mecânica, Minas Gerais – MG.
- [6] SIRQUEIRA, A. S., 2008, "Comportamento Estrutural de Torres de Aço Para Suporte de Turbinas Eólicas", Rio de Janeiro.
- [7] SIMIU, E.; Scalan, R.H.: "Wind Effects on Structures – Fundamentals and Applications Design", John Wiley & Sons. New York, 1996.
- [8] SLOOTWEG, J. G., et al., 2003, "General Model for Representing Variable Speed Wind Turbines in Power System Dynamics Simulations", IEEE Transactions on Power Systems, v. 18, n.1, pp. 144-151.
- [9] Zhou, M., Pagaldi, N., Thomas, H.L. and Shyy, Y.K., *An integrated approach to topology, sizing, and shape optimization. Struct Multidisc Optimiz*, Volume 26, 2004, 308-317.
- [10] Tahir Sağ, Mehmet Çunkaş, *A tool for multiobjective evolutionary algorithms*, Advances in Engineering Software, Volume 40, Issue 9, September 2009, Pages 902-912, ISSN 0965-9978.
- [11] A. Kaveh, S. Talatahari, *Particle swarm optimizer, ant colony strategy and harmony search scheme hybridized for optimization of truss structures*, Computers & Structures, Volume 87, Issues 5–6, March 2009, Pages 267-283, ISSN 0045-7949.
- [12] Vedat Toğan, Ayşe T. Daloğlu, *Optimization of 3d trusses with adaptive approach in genetic algorithms*, Engineering Structures, Volume 28, Issue 7, June 2006, Pages 1019-1027, ISSN 0141-0296.
- [13] Tayfun Dede, Serkan Bekiroğlu, Yusuf Ayvaz, *Weight minimization of trusses with genetic algorithm*, Applied Soft Computing, Volume 11, Issue 2, March 2011, Pages 2565-2575, ISSN 1568-4946.
- [14] Mustafa Sonmez, *Artificial Bee Colony algorithm for optimization of truss structures*, Applied Soft Computing, Volume 11, Issue 2, March 2011, Pages 2406-2418, ISSN 1568-4946.
- [15] Luh, Guan-Chun, Lin, *Optimal design of truss structures using ant algorithm*, *Structural and Multidisciplinary Optimization*, Volume 36, Issue 4, 2008, Pages 365-379, 1615-147X.
- [17] Kaveh, A. Shojaei, S., *Optimal design of skeletal structures using ant colony optimization*, International Journal for Numerical Methods in Engineering, Int. Volume 70, Issue 5, 2007, Pages 563-581, 1097-0207.
- [18] Holland, J. H., *Adaptation in Natural and Artificial Systems*, 1975, University of Michigan Press.
- [19] Ruiyi, Su and Liangjin, Gui and Zijie, Fan, *Truss Topology Optimization Using Genetic Algorithm with Individual Identification Technique*, 2009.
- [20] Norapat Noilublae and Sujin Bureerat. 2011. *Technical Note: Simultaneous topology,*

- shape and sizing optimisation of a three-dimensional slender truss tower using multiobjective evolutionary algorithms.* *Comput.Struct.* 89, 23-24 (December 2011),2531-2538.
- [21] PACHECO, M. A. C. *Algoritmos genéticos: princípios e aplicações.* ICA: Laboratorio de InteligenciaComputacionalAplicada, n. 1, jul. 1999.
- [22] M.R. Ghasemi, E. Hinton, R.D. Wood, (1999) "*Optimization of trusses using genetic algorithms for discrete and continuous variables*", *Engineering Computations*, Vol. 16 Iss: 3, pp.272 – 303.
- [23] Leandro Fleck Fadel Miguel, Rafael Holdorf Lopez, *Leticia Fleck Fadel Miguel, Multimodal size, shape, and topology optimisation of truss structures using the Firefly algorithm.* *Advances in Engineering Software*, Volume 56, February 2013, Pages 23-37, ISSN 0965-9978.
- [24] Josef Farkas, KarolyJarmai, *Optimum Design of Steel Structures*,Springer-Verlag Berlin Heidelberg; 2013; Chapter 5.
- [25] Hani M. Negm, Karam Y. Maalawi, *Structural design optimization of wind turbine towers.* *Comput.Struct*, Volume 74, Issue 6, 1 February 2000, Pages 649-666.
- [26] Wellison José de Santana Gomes, André Teófilo Beck, *Global structural optimization considering expected consequences of failure and using ANN surrogates.* *Computers & Structures*, Volume 126, 15 September 2013, Pages 56-68
- [27] Sinan Korkmaz, *A review of active structural control: challenges for engineering informatics.* *Computers & Structures*, Volume 89, Issues 23–24, December 2011, Pages 2113-2132

ACKNOWLEDGMENTS

The authors thank the generous support of the PontificiaUniversidadeCatolica de Minas Gerais – PUCMINAS, the ConselhoNacional de DesenvolvimentoCientifico e Tecnologico - CNPq - "National Counsel of Technological and Scientific Development" and Fundacao de Amparo a Pesquisa de Minas Gerais – FAPEMIG – "Foundation for Research Support of Minas Gerais".