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Towards automating the structural design of guyed masts

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Research Paper

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Towards automating the structural design of guyed masts

This paper presents the development of a MATLAB framework to automate the modelling, analysis, and design of anemometric guyed masts using the SAP2000 Open Application Programming Interface (OAPI). The framework adopts the current generation of Eurocode provisions and includes relevant loading cases. The efficiency of the OAPI is demonstrated through the analysis of two representative guyed masts with heights of 122 m and 164 m. Several design parameters are varied to identify the most favourable layouts in terms of steel consumption and execution time. The best initial mast layouts were selected, and potential improvements to the OAPI are highlighted.

Key words:
cable-supported structures, automated structural design, patch wind loading, OAPI-based structural analysis, nonlinear FEM

Znanstveni rad - Prethodno priopćenje

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Automatizacija konstrukcijskog projektiranja jarbola učvršćenih užadi

U radu prikazan je razvoj programskog okvira MATLAB za automatizaciju modeliranja, analize i projektiranja anemometrijskih jarbola učvršćenih užadi primjenom sustava SAP2000 Open Application Programming Interface (OAPI). Okvir koristi aktualne odredbe eurokoda i uključuje relevantne slučajeve opterećenja. Učinkovitost OAPI-ja prikazana je analizom dvaju reprezentativnih jarbola učvršćenih užadi visine 122 m i 164 m. Varirani su različiti projektni parametri kako bi se identificirala najpovoljnija rješenja s obzirom na potrošnju čelika i vrijeme izvedbe. Odabrane su najbolje početne konfiguracije jarbola te istaknute mogućnosti daljnjeg unaprjeđenja OAPI-ja.

Ključne riječi:
konstrukcije s užadi, automatizirano konstrukcijsko projektiranje, parcijalno opterećenje vjetrom, konstrukcijska analiza temeljena na OAPI-ju, nelinearna metoda konačnih elemenata

1. Introduction

Owing to the increasing demand for clean energy production in modern industries, large wind farms have been extensively designed and constructed in Serbia and the Western Balkans (WB) since the 2000s. The solar and wind capacity of the WB is 23 GW, which is comparable to that of Germany [1, 2]. Wind farm projects require a preliminary assessment of wind energy potential at future site locations, considering the planned height of the wind turbines (which may reach up to 160m). To meet these requirements, steel-guyed anemometer masts are frequently used to support lightweight equipment for measuring wind speed and direction at different altitudes. Guyed masts are very slender and tall spatial lattice structures consisting of:

- a vertical central mast shaft made of standard lattice segments,
- sets of inclined pre-tensioned high-grade steel guy ropes that laterally support the mast at different altitudes,
- a central mast foundation and anchoring blocks for guy ropes that are radially distributed around the mast (see Figure 1).

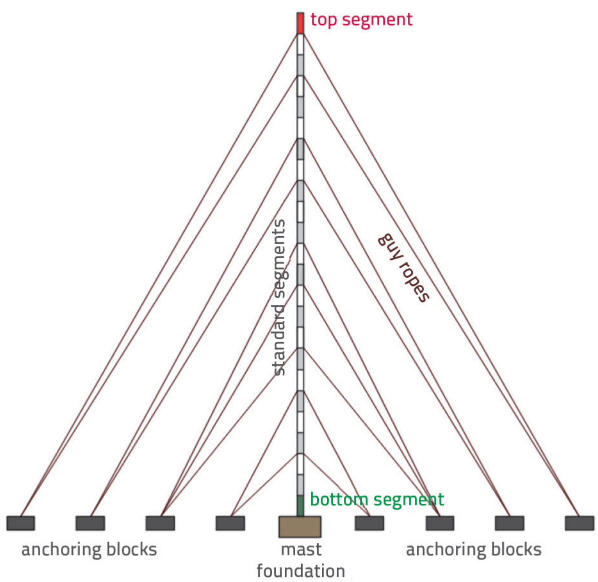


Figure 1. Main parts of the guyed mast layout

Standard lattice mast segments, typically 3 m long and 0.4–1.0 m wide, mostly comprise circular (tubular) leg members and welded horizontals and diagonals. These typically carry lightweight steel booms with side anemometers and wind vanes at various altitudes. The first (bottom) segment is connected to the central foundation, typically using a pinned connection, resulting in a (dominantly) axially loaded mast foundation. Such connections can be accomplished as pivoted or, more commonly, tapered bases [3]. A pinned guyed mast may require an anti-twist arm to provide additional torsional stability at the desired altitude. The last (top) segment carries only the top boom and lightning rod. Consequently, anemometric guyed masts do not require large or heavy frame sections and are inherently lighter than other mast types (i.e., for telecommunication purposes). Therefore, standard segments enable simplified handling and lifting operations, resulting in a faster and more reliable on-site erection process [4-6].

Tall-guyed mast structures exhibit inherently nonlinear behaviour owing to their slender geometry, tension-only cable systems, and nonlinear (large displacements) response under environmental loading. The key source of this nonlinearity lies in guy cables and their load-dependent stiffness, which has been within the scope of research for decades. Jayaraman and Knudson proposed an efficient (small-strain) elastic curved spatial cable element for analysing cable structures under point and distributed loads [7]. Three-dimensional cable element formulations based on exact analytical expressions of the elastic catenary, which are also applicable to thermal loads, were proposed in [8-10]. The interaction between the cable and frame elements was proposed by Coarita and Flores using a mixed algorithm [11], whereas Shi and Salim developed an original finite element (FE) framework [12], conducted a nonlinear study of the guyed mast, and validated the model by comparing the results with several commercial FE-based software packages.

The structural analysis of a guyed mast is a complex task that requires special engineering knowledge and experience because of:

- the nonlinear behaviour of both the guy cables and the mast,
- the relatively complex estimation of wind and ice loads,
- the dynamic nature of wind loading.

A complete nonlinear dynamic stochastic analysis of truss-guyed masts, although the most accurate, is time-consuming and usually requires specialised software. Therefore, considerable research effort has been invested in simplifying the analysis and design rules to enable the use of equivalent static analysis and obtain efficient structural layouts. Madugula et al. [13, 14] conducted analytical, experimental, and FE investigations using truss and beam-column models. The former includes detailed modelling of the lattice, whereas the latter is based on approximating the lattice using beam elements with equivalent axial, bending, shear, and torsion stiffnesses. They showed that a beam-column model is reliable and cost-efficient for both iced and ice-free masts and highlighted the low influence of torsion resistors on the overall dynamic response of the masts. Matuszkiewicz [15] analysed a guyed mast by considering the mast's imperfections, while Erdem [16] performed an 80 m guyed mast analysis in SAP2000 [17], elaborated the main analysis steps, and proposed recommendations for guy cable diameter selection.

Although the equivalent static analysis provides simplifications compared with complete dynamic stochastic analysis, the modelling and analysis of a guyed mast remain inherently challenging owing to its numerous structural components (particularly guy cables), broad spectrum of load cases, and strong interdependence between the adopted mast geometry and applied loads. Therefore, the essential step is to define an initial layout of the mast and its guying system that is as effective as possible, thereby minimising the need for extensive modifications during the subsequent modelling and analysis steps [18]. These challenges have prompted researchers to employ automated algorithms that enable the systematic exploration of design alternatives, moving beyond conventional experience-based and trial-and-error approaches. Since the pioneering work of Bell and Brown [19], numerous studies have addressed the optimisation of mast structures using various techniques [20-23]. These efforts have typically focused on optimising the mast geometry, guy configurations, and/or prestress forces in guy cables to reduce the total structural mass. However, for tall guyed masts, where the structural mass per unit length is relatively low, minimising self-weight is not necessarily the governing design criterion. Practical design experience has shown that other governing factors may be even more challenging, such as the efficiency of the on-site assembly (number of guy attachments through the height, number, and dimensions of anchoring blocks, number and weight of assembly parts, etc.). Furthermore, the aforementioned studies were generally limited to short masts with only a few guy levels, and they often neglected cable nonlinearity. In addition, ice loading was commonly omitted, further limiting the applicability of their findings to real tall mast structures.

This study presents an original framework that automates the modelling, FE analysis, and steel design utilisation checks required in the preliminary structural design of tall anemometric guyed masts. The framework was developed using MATLAB [24] and SAP2000's Open Application Programming Interface (OAPI). Similarly, Cucuzza et al. [25] utilised SAP2000 coupled with MATLAB through the OAPI to optimise the size and shape of a 30 m guyed mast. The structure comprised a single central circular hollow steel profile represented by beam elements, and the 21 supporting elements were modelled using SAP2000 cable elements. However, they modelled wind and ice actions following Italian national recommendations [26] rather than the relevant Eurocodes. The framework presented in this study adopts Eurocode-based provisions (current generation) for the design of guyed mast structures and includes relevant loading cases considering both wind and ice actions. Subsequently, a case study involving two tall pinned anemometric guyed mast layouts with varying prescribed sets of design parameters (steel grade, wind speed, and guy layout) was conducted to explore the most favourable mast design solutions. The target objectives were not only evaluated in terms of steel consumption, but also to minimise the execution time and simplify the layout. The analysis demonstrated that the developed OAPI reached the target objectives easily, according to the contractor's demands, by automatically evaluating hundreds of structural layouts according to the assigned constraints. Finally, possibilities for further improvements in the OAPI are highlighted. The framework has long-term applicability because it can be easily adapted to the upcoming second generation of Eurocodes.

2. Structural analysis and design of a guyed mast

In Serbia, structural steel design is performed according to the SRPS EN (Eurocode) set of standards, complemented by national annexes and necessary ISO standards, aligning Serbia with the European norms for structural design. When analysing the guyed mast, three criteria must be satisfied to ensure that an equivalent static analysis can be performed (maximum cantilever length, maximum ratio of mast and guy stiffnesses, and maximum ratio of guy mass to wind speed), according to SRPS EN 1993-3-1:2012 [27]. The procedure is based on mutually combined static patch wind loads.

2.1. Actions on the guyed mast structure

The characteristics and design values of the actions, as well as the load combinations, should be calculated in accordance with [28-30], considering the appropriate reliability class of the guyed mast. The following loads should be considered: the self-weight, additional dead load, guy prestressing, ice load, and wind load. Seismic action is not relevant because the maximum seismic force is several times lower than the force resulting from mean wind loading. The effects of snow and temperature are negligible compared with ice effects; thus, they may be omitted, especially in the conceptual design phase. The guy rupture load case is beyond the scope of this study.

The additional dead load originates from the mast equipment. Guy prestressing should be adopted in the range of 10–20 % of the minimum rope breaking force according to [31-32]. The effect of ice should be calculated according to [33] for the considered glaze ice-class (ICG). In addition to the additional dead loading, ice changes the dynamic behaviour of the mast and increases its wind drag coefficient. Wind actions on the mast should be determined according to [27, 29], accounting for the fundamental wind velocity $v_{b,0}$ and the appropriate terrain type and orography factor c_o. The total wind effect on the mast structure and guy cables should be calculated as the sum of the equivalent static actions of the *mean wind* load and the fluctuating component due to wind gusts (*patch wind* load) for all considered wind directions [27].

Both the mean wind load on the mast $F_{m,W}$ and the mean wind load on the guy cables $F_{G,W}$ are functions of the peak velocity pressure $q_p(z)$, turbulence intensity $I_v(z)$, wind force coefficients $c_W(z)$ and $c_{f,G}(z)$ in the considered wind direction, and the corresponding projected areas of either the mast or the guy cables. The reference height z was adopted as the altitude at the top of the considered mast segment. For simplicity, a uniform load distribution along the guy may be adopted, with the wind pressure determined for z=2H_i/3 (H_i is the height of the i^{th} guy attached to the mast).

Successive patch wind loads should be assigned to both the mast sections and the guys [27]. The number of patches depends on the number of guy levels. The patch load on the guy can be smeared over the entire length. Then, the forces due to patch loads $S_{p,Li}$ are calculated as the difference between the forces due to the combined mean and patch wind loads and those induced by the mean wind load alone. The total effect of the wind patch load S_p was then obtained by combining the individual effects of all patch wind loads $S_{p,Li}$, Eq (1):

$$S_P = \sqrt{\sum_{i=1}^{N} S_{P,Li}^2} \tag{1}$$

where N is the total number of patch-loaded cases.

The overall effect of wind load S_T is equal to the envelope of the following loads:

$$S_T = S_M \pm S_P \tag{2}$$

where S_M is the effect of the mean wind load.

The calculation of the wind effects for the iced structure is similar to that for the ice-free case, with changes in structural thickness and appropriate drag coefficients. The effects of ice and wind were combined in two ways:

- dominant wind (high probability of occurrence) with associated ice (low probability)
- dominant ice (high probability of occurrence) with associated wind (low probability).

The coefficient k introduced in [33] reduces the wind pressure on the ice structure for the ice class considered.

2.2. Considered design checks

In the preliminary design, when an engineering decision is made on the mast layout, the ultimate limit state (ULS) and stability checks [30] of the mast legs should be performed first, based on the forces obtained from the structural analysis. Then, a ULS check [32] of the guy cables is performed. The minimum cable breaking force F_{uk} for guy cables should be determined based on the selection of the terminations of the steel wire ropes (i.e. thimbles [34] and U-bolt grips [35]). In this study, a flexural buckling design check of the mast legs, according to [30], Section 6.3, was performed, followed by a ULS check of the cables according to [32] (Section 6.2).
After the structural layout is adopted and the main members are checked, the secondary mast members (horizontal and diagonal) are designed, along with the joints according to [36] and foundation design [37], which are beyond the scope of this study.

3. Development of SAP2000 OAPI using MATLAB

In this study, an equivalent beam-column model of the mast supported by guy cables at different altitudes was considered in SAP2000. The central mast was modelled using spatial frame elements (with six DOFs per node), whereas the cables were modelled using spatial cable elements (with catenary and tension-only behaviour, axial stiffness, and no bending or shear stiffness). The self-weights of the mast legs and cables were assigned automatically, whereas the additional self-weight originating from the horizontal and diagonal elements of the mast was assigned as appropriately distributed load. The initial prestressing forces were assigned to the cables (cable tension at the anchoring block). As defining the cable tension in the Cable Geometry form does not generate a prestressing force, the target force load case was set to achieve the target pretension in the cables. Ice loading was calculated and assigned as an equally distributed gravity load, while mean and patch wind loads were assigned as distributed load patterns in the considered directions for both the iced and ice-free cases. Finally, all load combinations according to [27] were generated as independent nonlinear-static load cases (without the superposition principle), considering the structural stiffness from the previous loading cases and P-effects. Finally, default nonlinear solver settings were adopted (200 steps per stage, 40 Newton-Raphson iterations per step, tolerance = 0.0001, 10 target force iterations, and target force tolerance = 0.01).
This emphasises the complexity of determining the optimal layout of the guyed mast, which further increases with an increase in the total mast height. Therefore, for masts higher than 100 m, considerable engineering effort must be invested in the conceptual design phase to determine the optimal solution from hundreds of possible layout combinations. In engineering practice, manual modelling typically leads to a time-consuming trial-and-error process with repetitive design checks of the adopted layout. Because wind loads are highly dependent on the mast layout, especially on the number and arrangement of guy cables, evaluating alternative layouts also requires continuous updates to load analysis. The absence of a superposition principle makes the conceptual design even more challenging. Finally, manual modelling may introduce unintended input errors during data entry. Owing to the highly nonlinear structural behaviour of guyed mast systems, such errors are not always easily detected in analysis results.
A sensible solution is the automation of the structural design process using an Open Application Programming Interface (OAPI) developed in MATLAB. The OAPI is integrated with SAP2000 and efficiently performs the automation process (see Figure 2). Consequently, the generated models were identical to those created manually in the SAP2000 GUI, including the element types, connectivity, boundary conditions, loading definitions, and analysis settings. Structural analysis was performed using

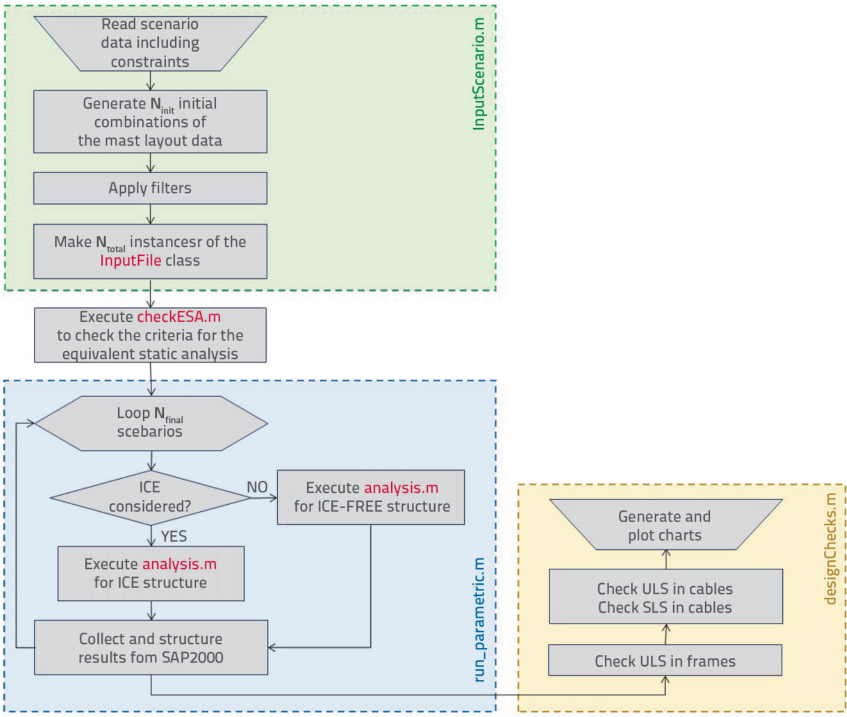


Figure 2. A flowchart of the automated process in finding the best initial mast layout

Table 1. Overview of the wind turbines' properties in the wind farm projects in Serbia

Wind farm	Hub height [m]	Number of turbines	Phase
Plandište [38]	151	17	ready to build
Pupin [39]	118	16	in operation
Kovačica [40]	120	38	in operation
Kostolac [41]	114	20	trial run
Čibuk 1 [42]	110	57	in operation
Čibuk 2 [43]	138	22	under construction
Vetrozelena [44]	120	48	ready to build
Crni vrh [45]	130	28	under construction
Krivača [46]	105	22	in operation
Alibunar [47]	100	21	in operation
Malibunar [48]	100	4	in operation
Košava I [49]	110	20	in operation

the same SAP2000 solver, meaning that automation replaced only the manual model generation process without altering the underlying analysis procedure. The proposed framework eliminates input errors by generating structural models and analyses in a consistent and systematic manner, thereby ensuring improved modelling consistency.

Within the workflow, the InputScenario.m script loads the input data regarding the mast geometry, wind speed, ice class, and assigned constraints. It generates N_{init} combinations of the mast layout data and filters them by applying constraints (details are given in Section 4). After filtering, N_{total} combinations are adopted, the equivalent static analysis criteria fulfilment is checked using checkESA.m, and N_{final} possible instances of the InputFile class are generated for further analysis (this class stores the entire data of the considered scenarios).

run_parametric.m is responsible for running the analysis of all N_{final} layout combinations, considering both ice- and ice-free cases, and collecting and structuring the results, while the analysis is the core of the OAPI. First, all functions responsible for communication with SAP2000 were invoked, enabling the automated creation of materials, frames, and cables; assignment of frame and cable sections; application of loads within defined load patterns (dead load, ice, target force, mean, and patch wind loads); and generation of nonlinear load cases and load combinations. For this purpose, OAPI generates the instances of the FrameElement, SingleCable and DoubleCable classes, and calls the necessary methods of the WindLoad class. After the model is generated, analysis.m executes the SAP2000 analysis for both ice- and ice-free cases and finally calls the utility functions for passing the necessary results (frame and cable forces) from SAP2000 to MATLAB variables. The results were evaluated within designChecks.m through the necessary design checks (ULS in the mast legs and cables), and the utilisation ratios U_R defined with respect to the selected steel grade were derived and used to evaluate the efficiency of the considered mast layout.

4. Considered case studies

First, an analysis of wind turbine heights for wind farms in Serbia was conducted. Table 1 lists the turbine heights installed on wind farms in Serbia, which were in different developmental phases. The earliest wind farms in Serbia predominantly employed turbines with heights of up to 120 m, whereas several upcoming wind farm projects are expected to install turbines with heights of up to 160 m. Therefore, two case studies considering 122 m and 164 m masts (CS1 and CS2, respectively) are presented in this section.

The primary objective of the case studies was to compare the efficiencies of different mast layouts (through the ULS utilisation rates, total cable length, and necessary number of anchoring blocks) by varying the following input parameters: number of guy levels, guy attachment altitude H_i, anchoring block distance R_i and mast steel grade (S235–S355). Structural parameters, such as mast height, mast cross-section, mast segment layout, and cable diameter, as well as load parameters, including fundamental wind velocity, ice class, and percentage of ancillary equipment, were predefined and held constant throughout the case studies (Table 2).

The design value of the wind load was calculated for the three characteristic wind directions, as shown in Figure 3. A triangular mast layout was selected because it has a lower wind incidence factor K_θ and lower wind force coefficients $c_{f,s,0}$ than a square layout [27]. Reliability class 1 (*towers and masts built on unmanned sites in open countryside; towers and masts, the failure of which would not be likely to cause injury to people*) was considered, according to [27]. Circular leg members were selected because their drag (pressure) coefficients were more than twice those of flat members. Note that solid circular leg members (selected in CS1) generate lower wind loads on the mast shaft and thus lower compression forces in the legs, but also have lower flexural buckling resistance $N_{b,Rd}$ [30] in comparison to circular hollow sections (CHS), selected in CS2.

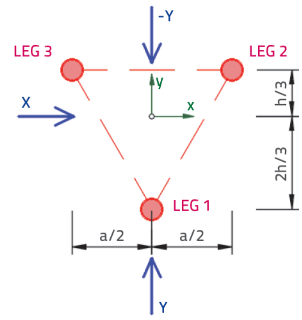
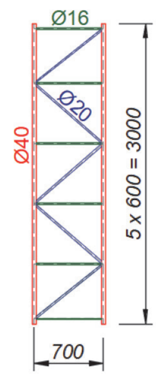
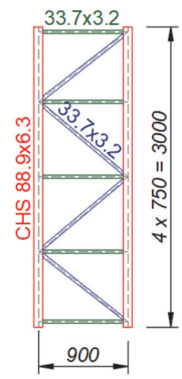


Figure 3. Considered wind directions for the triangular mast layout

For CS1, a location with $v_{b,0}$ = 25 m/s, and ICG-2 ice class was selected, whereas for CS2, $v_{b,0}$ = 29 m/s (maximum for Serbia)

Table 2. Overview of the mast input data and applied constraints in CS1 and CS2

Data	Property	Case study 1	Case study 2
Mast input data	Reliability class	1	1
	Mast cross section and segment layout		
	Cable diameter	12 mm	14 mm
	Fundamental wind velocity $v_{b,0}$	25 m/s	29 m/s
	Ice-class	ICG – 2	ICG – 2
	Mast height H_{total}	122 m	164 m
	Ancillary equipment percentage A_A/A_S	20 %	10 %
Assigned constraints	First guy attachment level H_1	12 m	12 m
	Min spacing between guy levels $\Delta H_{i,min}$	9 m	12 m
	Max spacing between guy levels $\Delta H_{i,max}$	15 m	15 m
	Max difference in guy level spacings max (ΔH_i - ΔH_j)	3 m	3 m
	Minimum number of guy attachments per anchoring block $N_{a,min}$	2	2 – Single cable 1 – Double cable
	Maximum difference in the number of guy cables per anchoring block max ($N_{ai} - N_{aj}$)	1	1
	Min guy inclination angle α_{min}	30°	30°
	Max guy inclination angle α_{max}	70°	70°
	Min anchoring block–mast distance $R_{i,min}$	10 m	20 m
	Max anchoring block-mast distance $R_{i,max}$	50 m	80 m
	Maximum adjacent anchoring blocks spacing ΔR_i	20 m	20 m

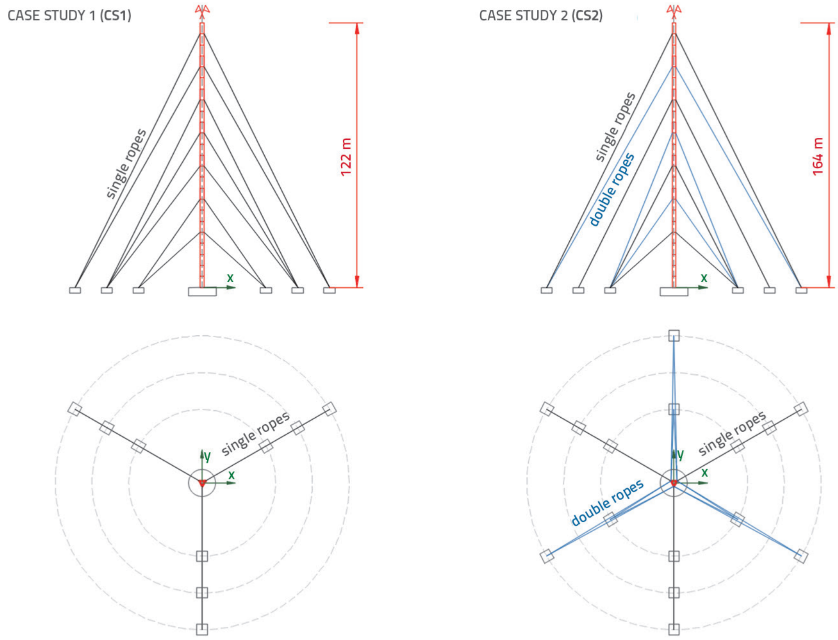


Figure 4. Considered guy layouts

the guy layout, two options were considered in this study: three guys per level (CS1) and alternately three or six guys per level (CS2) (Figure 4). The second option requires additional anchoring blocks and more guy cables, but it more effectively prevents torsion of the mast and provides a more uniform force distribution.

The geometry of each guy cable was defined by two coordinates: the attachment level on the mast and the point on the anchoring block. These coordinates are subject to specific geometric and practical requirements and, therefore, cannot be chosen arbitrarily. By changing the layout of the guy cables, the spacing between the guy levels, guy inclination angle, and horizontal distance between the anchoring blocks and mast are systematically altered but constrained within rational ranges, as defined in Table 2. The maximum altitude of the first guy attachment was H_1 = 12m, while a maximum difference of 3 m between the shortest and longest guy length was selected.

and ICG-2 were selected. Although the discrete ancillary items on the structure were almost negligible, their area A_A was adopted as 20 % (CS1) or 10 % (CS2) of the structural area A_S in the absence of more accurate data. For simplicity, the weight of the equipment was omitted.

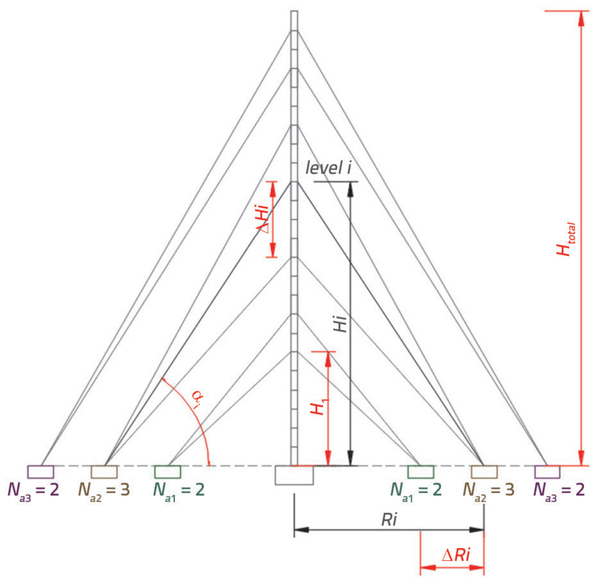


Figure 5. Illustration of the mast input data, assigned constraints, and varying parameters

In both case studies, steel spiral strand ropes of type 1 × 19 with a nominal tensile strength of 1570 N/mm^2, unit weight w = 830 × 10^{-7} N/mm^3, fill factor f = 0.76, modulus of elasticity E_Q = 150 GPa (140 GPa for load cases including ice), and breaking force factor K = 0.525, according to [32], were used. Regarding

Regarding the anchoring block layout, a minimum of two attachments per block ($N_{a,min,single}$ = 2) were selected for single ropes, whereas for double ropes (CS2), there was no limitation ($N_{a,min,double}$ = 1). To provide a relatively even distribution of reaction forces in the anchoring blocks, the maximum number of guy attachments per block was limited to one more than the minimum number in the considered layout. For example, a layout may have anchoring blocks with two, three, or four, or four or five guy cables, but a layout with 2–4 guys per block is not acceptable. The maximum distance between two anchoring blocks is limited to 20 m, while the blocks may be located at distances divisible by 10 m from the central foundation to simplify the layout.

5. Results and discussion

The mast input data presented in Table 2 led to N_{init} = 167,460 raw combinations of the mast layout data (CS1) or N_{init} = 750,918 combinations for CS2. Subsequently, based on the assigned constraints (see Section 4 and Table 2 for details), the automated filtering procedure implemented within the OAPI generated a total of N_{final} = 5208 (CS1) and N_{final} = 2729 (CS2) possible mast layouts. The corresponding structural models were generated and calculated using the OAPI (Figure 2). The necessary ULS design checks were performed and used to evaluate the efficiency of the considered mast layout. As the steel grade did not influence the analysis results, design checks were performed for three different steel grades after the analysis results were collected. The feasible configurations that passed the ULS design check for both the mast and cables were collected for all steel grades, and the evaluation results were plotted.

Figure 6 illustrates the obtained mast-leg ULS utilisation ratios U_R for CS1, considering the necessary number of anchoring blocks N_{ab}, total cable length L_g, number of guy levels, and different steel grades. As expected, increasing the steel grade increased the number of feasible mast layouts: 373 (7 %) for S235 and 4116 (79 %) for S275 and S355; all layouts (100 %) passed the ULS design check. Steel S235 provided a relatively low structural reserve (U_R > 95.67 %), whereas for S275 U_R > 85.33 %, and for S355 U_R > 71.88 % (note that U_R > 85 % is plotted using bold dots for clarity). The structural reserve means that the initially selected layout may be further optimised by reducing both the cross sections of the mast structure and the number of men.

For the assigned constraints, a feasible structural layout may be achieved using 9, 12, or 15 anchoring blocks and 9 to 13 guy levels, resulting in a total nominal cable length of 1924 to 2684 m. The S235-based layout that minimises the execution time, which is characterised by a reduction in the number of anchoring

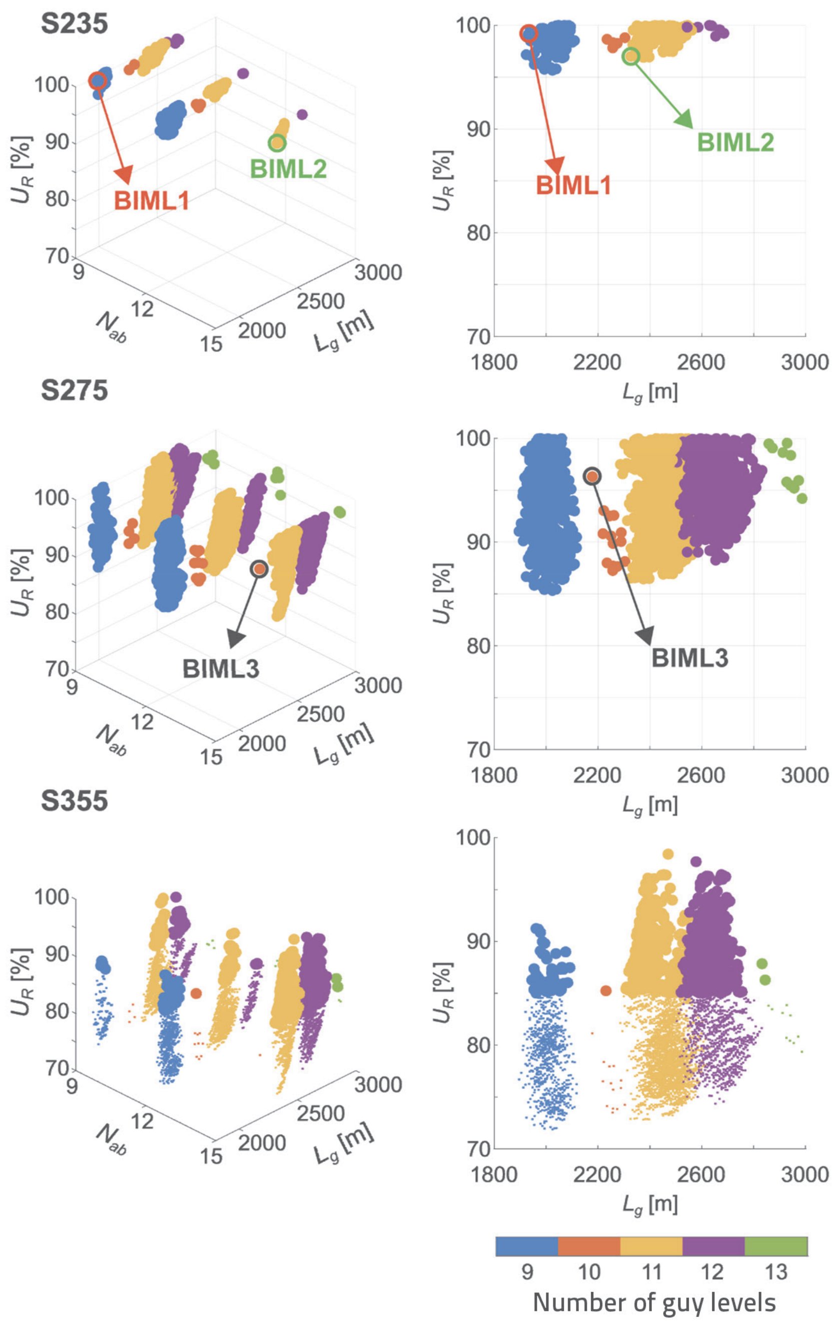


Figure 6. ULS utilisation ratios (U_R) for the CS1, considering different steel grades, the necessary number of anchoring blocks (N_{ab}), total cable length (L_g), and the number of guy levels

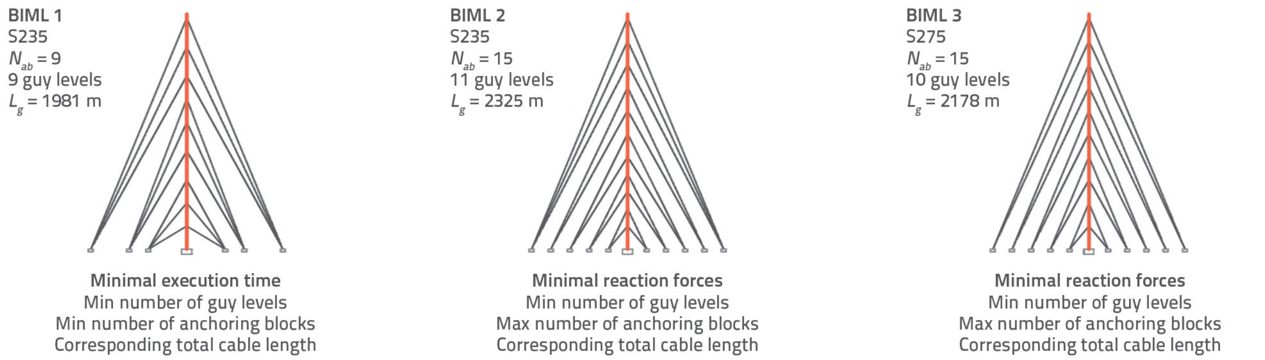


Figure 7. Best initial mast layouts selected in the CS1

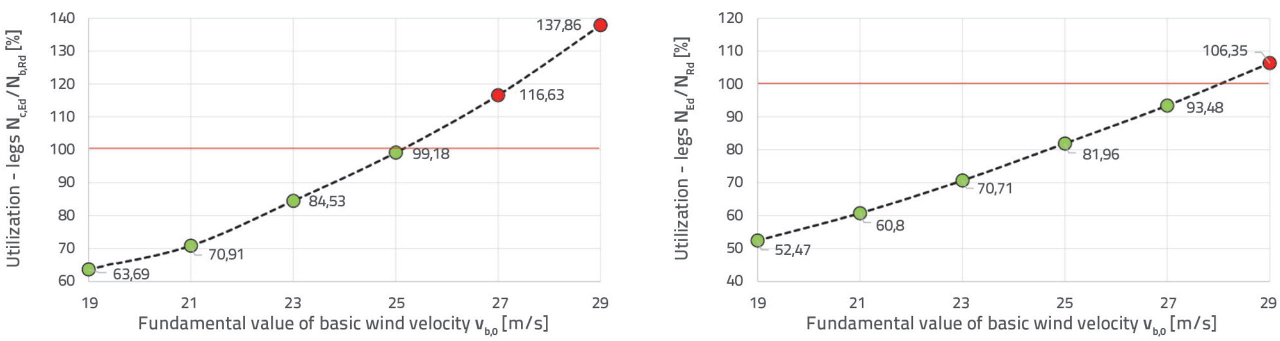


Figure 8. ULS utilisation ratios for mast legs (left) and cables (right) of the BIML1 configuration

blocks and guy levels, can be achieved with a wide range of total guy lengths. A layout featuring a minimal number of anchoring blocks (9), minimal attachment levels (9), and the corresponding minimal total length of the guys (1981 m) is labelled as BIML1 (Best Initial Mast Layout 1) as shown in Figure 7. The utilisation ratio for BIML1 was 99.18 % (Figure 6, row 1, middle panel).

A smaller number of anchoring blocks leads to higher reaction forces at each foundation point, which requires good soil conditions. If the site is characterised by relatively poor soil properties, a design with a higher number of anchoring blocks (a maximum of 15) may be more appropriate. In such cases, the most suitable S235-based layout comprises 11 guy levels (again minimising execution time) and a total guy length of 2325 m, and this layout is labelled BIML2 (see Figures 6 and 7 for the evaluation and layout illustration, respectively).

The number of guy levels may be further reduced to 10 (which would slightly accelerate the execution) using the S275 steel grade, resulting in a slight reduction in the total guy length to L_g = 2178 m when compared to BIML2 (see BIML3 in Figures 6 and 7).

The structural reserve was illustrated by assessing the influence of the fundamental value of the basic wind velocity $v_{b,0}$ on the utilisation ratios of both the mast legs and cables of the BIML1 configuration. Since it was shown that S235 provides relatively low structural reserve, the selected layout cannot be used for the locations with higher wind speeds, as shown in Figure 8, and $v_{b,0}$ = 25 m/s is an upper bound for the selected mast layout within CS1.

Finally, CS1 was repeated with an increased fundamental wind velocity of $v_{b,0}$ = 29 m/s. The analysis showed that no single layout could pass the ULS utilisation check for the selected mast geometry, cable diameter of 12 mm, and assigned constraints. Further analysis showed that $v_{b,0}$ = 28 m/s was the upper bound for the selected mast layout in CS1 (see Table 2 for details).

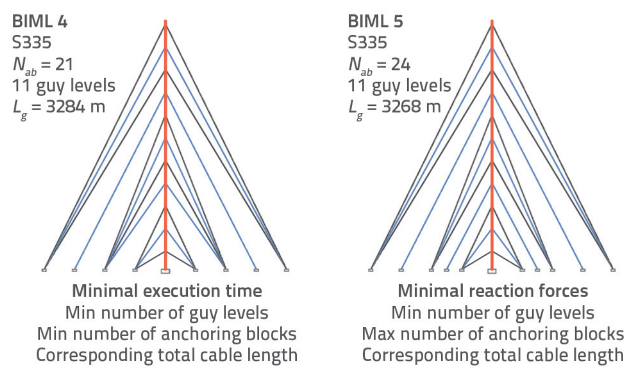


Figure 9. ULS utilization ratios (U_R) for the CS2, considering the necessary number of anchoring blocks (N_{ab}), total cable length (L_g), and number of guy levels, for S355

Figure 9 illustrates the evaluation results for CS2. Because higher $v_{b,0}$ and H_{total} were set, only S355 provided a successful ULS design check, with 1036 feasible layouts (38.0 %). Because the preliminary study showed that 12 mm cables were inadequate for the considered $v_{b,0}$

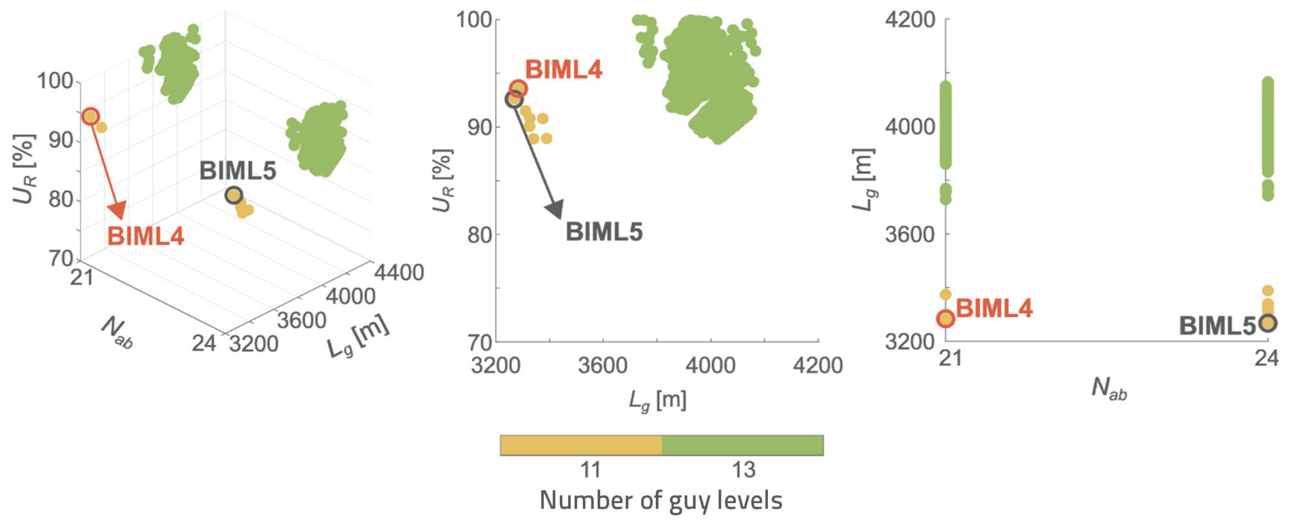


Figure 10. Best initial mast layouts selected in the CS2 (black–single ropes, blue–double ropes)

and H_{total}, CS2 involved single and double 14 mm cable ropes (see Table 2). Figure 9 also shows that there is a relatively low structural reserve (U_R > 88.86 %); thus, a limited reduction in the cross sections of the mast structure is possible. For the assigned constraints, a feasible structural layout may be achieved using 21 or 24 anchoring blocks and 11 or 13 guy levels, resulting in a total nominal cable length of 3268 to 4166 m. The minimum number of anchoring blocks (21), the minimum number of guy levels (11), and the corresponding minimal total guy length of 3284 m are achieved with mast layout 4 (BIML4), as shown in Figures 9 and 10. Lower reaction forces in the anchoring blocks may be achieved by using 24 anchoring blocks combined with 11 mast levels, resulting in a total length of 3268 m (see BIML5 in Figures 9 and 10).

6. Conclusions

Modelling tall guyed masts is inherently challenging. The use of equivalent static analysis and a simplified beam-column representation of the mast, rather than a full nonlinear dynamic analysis and detailed lattice model, significantly simplifies the modelling process of these structures. However, the large number of guy cables, the wide range of load cases, and the strong interdependence between them still require substantial time and effort in the early stages of design.

An original MATLAB framework that automates this process is presented. It features automated modelling and FE analysis in SAP2000 through OAPI and steel design utilisation checks required for the structural design of tall anemometric guyed masts. The mast structure was modelled using an equivalent beam-column model and all relevant load-case scenarios, including both ice- and ice-free cases. The OAPI loads the input data regarding the mast geometry, wind speed, ice class, and assigned constraints; generates possible combinations of the mast layout data; filters them by applying the constraints; and checks the fulfilment of the equivalent static analysis criteria. Then, the OAPI analyses all feasible layout combinations, collects and structures the results, and evaluates them through necessary design checks.

The efficiency of the developed OAPI framework is demonstrated through two case studies involving 122 m and 164 m-tall guyed masts (CS1 and CS2, respectively). These cases investigated variations in the layout of guy cables and identified the most suitable configurations for the considered design conditions. The execution time for a guyed mast structure is closely related to the number of attachment levels and anchoring blocks. Therefore, the most efficient construction is achieved when both parameters are minimised.

The present study highlights the advantages of automating the design process for analytically complex structures such as guyed masts. The proposed framework enables the exploration and evaluation of numerous possible configurations, thereby enabling engineers to identify the most suitable solutions for further design stages. So far, the developed framework has accounted for variations in guy layouts. Future work should extend this approach to include additional input parameters, such as the guy diameter and mast geometry (such as leg distance and cross-sectional dimensions). The incorporation of the full set of design checks required for each configuration enables a fully automated design process.

The developed framework is built around the current generation of Eurocode standards, but can be easily adapted to the upcoming second generation of Eurocodes. The second generation will include EN 1991-1-9: atmospheric icing on structures, which is based on the currently used ISO standard [33]. In addition, SRPS EN 1993-3-1 [27] and SRPS EN 1993-3-2 [49] will be merged, but the analysis approach for guyed masts will remain unchanged, and the tool's long-term applicability will be provided.

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REFERENCES

[1] Balkan Green Energy News, https://balkangreenenergynews.com/western-balkans-have-as-many-prospective-solar-wind-projects-as-germany, 28.12.2025.

[2] Nielsen, M.G., Støttrup-Andersen, U.: Design of guyed masts, 2nd Latin American Symposium on Tension Structures, Caracas, 2005.

[3] Marjanović, M., Milojević, M., Jočković, M.: Important aspects in design of anemometric steel masts in the Republic of Serbia, Proceedings of the 16th Congress hosted by Association of Structural Engineers of Serbia, Aranđelovac, Serbia, (2022), pp. 492–503.

[4] Jiang, W.Q., Wang, Z.Q., McClure, G., Wang, G.L., Geng, J.D.: Accurate modeling of joint effects in lattice transmission towers, Engineering Structures, 33 (2011) 5, pp. 1817–1827.

[5] Zhuge, Y., Mills, J.E., Ma, X.: Modelling of steel lattice tower angle legs reinforced for increased load capacity, Engineering Structures, 43 (2012), pp. 160–168.

[6] Erdem, R.T.: Analysis of guyed steel lattice mast subjected to environmental loads, GRAĐEVINAR, 67 (2015) 7, pp. 681-689, https://doi.org/10.14256/JCE.1181.2014

[7] Jayaraman, H.B., Knudson, W.C.: A curved element for the analysis of cable structuresa, Computers & Structures, 14 (1981) 3-4, pp. 325–333.

[8] Thai, H.T., Kim, S.E.: onlinear static and dynamic analysis of cable structures, Finite Elements in Analysis and Design, 47 (2011), pp. 237–246.

[9] Ahmad Abad, M.S., Shooshtari, A., Esmaeili, V., Riabi, A.N.: Nonlinear analysis of cable structures under general loadings, Finite Elements in Analysis and Design, 73 (2013), pp. 11–19.

[10] Choi, D.H., Gwon, S.G., Nassif, H.: Three-dimensional parabolic cable element for cable-supported structures, IAB SE Symposium Report, 102 (2014) 39, pp. 411–414.

[11] Coarita, E., Flores, L:. Nonlinear Analysis of Structures Cable – Truss, IACSIT International Journal of Engineering and Technology, 7 (2015) 3, pp. 160–169.

[12] Shi, H., Salim, H.: Geometric nonlinear static and dynamic analysis of guyed towers using fully nonlinear element formulations, Engineering Structures, 99 (2015), pp. 492–501.

[13] Madugula, M., Wahba, Y., Monforton, G.: Dynamic response of guyed masts., Engineering Structures, 20 (1998) 12, pp. 1097–1101.

[14] Wahba, Y., Madugula, M., Monforton, G.: Effect of icing on the free vibration of guyed antenna towers, Atmospheric Research, 46 (1998), pp. 27–35.

[15] Matuszkiewicz, M.: Calculation of guyed masts in accordance with EN 1993-3-1 standard taking into account mast shaft geometrical imperfections, Engineering Structures, 33 (2011), 2044–2048.

[16] SAP2000, Integrated Finite Element Analysis and Design of Structures Basic Analysis Reference Manual,Computers and Structures Inc. Berkeley, 1995.

[17] Belavičius, R., Jatulis D., Šešok D.: Some insights on the optimal schemes of tall guyed mast. Journal of Civil Engineering and Managementt, 19 (2013) 5, pp. 749–758.

[18] Bell, L.C., Brown, D.M.: Guyed Tower Optimization, Computers & Structures, 6 (1976), 447–450.

[19] Belavičius, R., Jatulis, D., Šešok, D.: Optimization of tall guyed masts using genetic algorithm, Engineering structures, 56 (2013), 239–245.

[20] Belavičius, R., Jatulis, D., Rusakevičius, D.: Optimal Schemes of Tall Pinned Masts, KSCE Journal of Civil Engineering, 28 (2024) 2, pp. 904–915.

[21] Cheng, J., Shi, T.: Structural optimization of transmission line tower based on improved fruit fly optimization algorithm, Computers and Electrical Engineering, 103 (2022), Paper No. 108320.

[22] Couceiro, I., París, J., Martínez, S., Colominas, I., Navarrina, F., Casteleiro, M.: Structural optimization of lattice steel transmission towers, Engineering Structures, 117 (2016), pp. 274–286.

[23] MathWorks: MATLAB Documentation, The MathWorks Inc., Natick, MA, 2025.

[24] Cucuzza, R., Rosso, M.M., Aloisio, A., Melchiorre, J., Giudice, M.L., Marano, G.C.: Size and Shape Optimization of a Guyed Mast Structure under Wind, Ice and Seismic Loading, Applied Sciences, 12 (2022), Paper No. 4875.

[25] CNR – Consiglio Nazionale delle Ricerche: Istruzioni per la valutazione delle azioni e degli effetti del vento sulle costruzioni, CNR-DT 207/2008, Rim, 2008.

[26] Institute for Standardization of Serbia: SRPS EN 1993-3-1: Eurocode 3 – Design of steel structures – Part 3-1: Towers, masts and chimneys – Towers and masts, Belgrade, 2012.

[27] Institute for Standardization of Serbia: SRPS EN 1990: Eurocode – Basis of structural design, Belgrade, 2012.

[28] Institute for Standardization of Serbia: SRPS EN 1991-1-4: Eurocode 1 – Actions on structures – Part 1-4: Wind actions, Belgrade, 2012.

[29] Institute for Standardization of Serbia: SRPS EN 1993-1-1: Eurocode 3 – Design of steel structures – Part 1-1: General rules, Belgrade, 2012.

[30] Institute for Standardization of Serbia: SRPS EN 12385-4: Steel wire ropes – Safety – Part 4: Stranded ropes for general lifting applications, Belgrade, 2009.

[31] Institute for Standardization of Serbia: SRPS EN 1993-1-11: Eurocode 3 – Design of steel structures – Part 1-11: Tension components, Belgrade, 2012.

[32] ISO: ISO 12494: Atmospheric icing of structures, International Organization for Standardization, Geneva, 2017.

[33] Institute for Standardization of Serbia: SRPS EN 13411-1: Terminations for steel wire ropes - Safety - Part 1: Thimbles for steel wire rope slings, Belgrade, 2009.

[34] Institute for Standardization of Serbia: SRPS EN 13411-5: Terminations for steel wire ropes - Safety - Part 5: U-bolt wire rope grips, Belgrade, 2012.

[35] Institute for Standardization of Serbia: SRPS EN 1993-1-8: Eurocode 3 - Design of steel structures - Part 1-8: Design of joints, Belgrade, 2012.

[36] IInstitute for Standardization of Serbia: SRPS EN 1997-1: Eurocode 7 – Geotechnical design – Part 1: General rules, Belgrade, 2010.

[37] Wind Park Plandiste, https://wpp.rs, 29.12.2025.

[38] Wind Park Pupin, https://vppupin.rs, 29.12.2025.

[39] Wind Park Kovačica, https://www.vpkovacica.rs/vetropark-kovacica, 29.12.2025.

[40] Wind Park Kostolac, https://www.prangl.com/projects/kostolac-wind-farm, 29.12.2025.

[41] A Tesla Wind Company, https://www.teslawind.rs/en, 29.12.2025.

[42] Wind Park Čibuk 2, https://cibuk2.rs, 29.12.2025.

[43] Wind Park Vetrozelena, https://vetrozelena.com, 29.12.2025.

[44] EL&MI Group, Wind Park Crni vrh, https://elmigroup.rs/en/energetika/crni-vrh-wind-farm, 29.12.2025.

[45] MK Group, Wind Park Krivača, https://mkgroup.rs/en/projects/krivaca-wind-park, 29.12.2025.

[46] Elicio, VP Alibunar, https://elicio.rs/en/wf-alibunar, 29.12.2025.

[47] Elicio, VP Malibunar, https://elicio.rs/projekat-malibunar, 29.12.2025.

[48] Fintel Energija AD, https://www.fintelenergija.rs/en, 29.12.2025.

[49] Institute for Standardization of Serbia: SRPS EN 1993-3-2: Eurocode 3 – Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys, Belgrade, 2012.