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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Structural and economic feasibility analysis of a 3.4 MW wooden wind turbine

LAUREA MAGISTRALE IN ENERGY ENGINEERING - INGEGNERIA ENERGETICA

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1. Introduction

The purpose of this thesis is to assess the feasibility of a wooden wind turbine from multiple perspectives. The study begins with the structural analysis, which represents the core of the project. Subsequently, rotor performance and control aspects are discussed, and finally a techno-economic analysis is carried out to evaluate the economic implications of replacing traditional materials with wood.
Starting from the IEA 3.4 MW reference turbine (techinical report available at [2] and Excel-based datasheet at [5]), a new wooden configuration is developed. The reference turbine features a blade length of 63 m, while the hub is located at 110 m. The turbine operates between a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s.

2. Structural analysis

The structural feasibility proved to be the most challenging and critical aspect of the entire project. The main limitation of wood lies in its lower mechanical strength compared to conventional materials typically used in wind turbine construction. Both the tower and the blades were analyzed. In this section, the adopted wood material model and the methodology used to perform the structural analysis are described.

2.1. Wood model

Wood was modeled as an orthotropic material, since its natural fibers (tracheids) exhibit a very high aspect ratio and are aligned along a preferential direction. As a consequence, the mechanical properties parallel to the tracheids are significantly higher than those in the transverse directions.
The adopted mechanical properties were obtained from experimental results on Norway spruce reported in a PhD thesis available online ([4]). Due to its characteristic microstructure, wood properties are conventionally defined with respect to the natural growth rings. As shown in Figure 1, the three principal material directions are denoted as L (longitudinal), R (radial), and T (tangential).

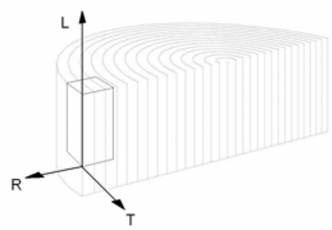

Figure 1: Reference frame of wood.

The elastic orthotropic model is defined via nine parameters, three for each direction, which are Young's coefficient (E), Poisson's coefficient (ν) and shear coefficient (G). The values adopted are reported in the following table. Note that the directions are marked by two characters, because ν and G are defined in a plane.

Orthotropic elastic coefficients

E $[GPa]$	ν $[-]$	G $[GPa]$
9.040 (LL)	0.42 (LR)	0.682 (LR)
0.790 (RR)	0.48 (LT)	0.693 (LT)
0.340 (TT)	0.5 (RT)	0.049 (RT)

Table 1: Coefficients of the orthotropic elastic model.

The strength parameters required for the failure prediction model were then defined. In wood, tensile and compressive strengths differ significantly and must be treated separately, together with the shear strengths. These values define the boundary between the linear elastic regime and the onset of nonlinear behavior. Therefore, the adopted material model can be considered linear elastic up to failure.

Orthotropic strength coefficients

σ_t $[MPa]$	σ_c $[MPa]$	τ $[MPa]$
63.4 (LL)	28.9 (LL)	6.1 (LR)
4.9 (RR)	3.6 (RR)	4.4 (LT)
2.8 (TT)	3.8 (TT)	1.6 (RT)

Table 2: Coefficients of the orthotropic strength.

Since the wooden turbine is supposed to be made of many lumber beams jointed together, the properties in direction (and planes) orthogonal to L were averaged each other, assuming that the beams would be placed with a random R or T direction. These parameters are quite in accord to the values obtainable by other sources, like [6] or [7].
Finally, the failure criterion was defined. According to the literature, the most suitable criterion for orthotropic materials is the Tsai-Wu criterion, an energy-based formulation widely used for composite materials. The criterion can be expressed as:

$$F_{TW} = F_{ii}\sigma_{ii} + F_{ijkl}\sigma_{ij}\sigma_{kl} \tag{1}$$

Where $\{i, j, k, l\} = \{L, R, T\}$, and the equation 1 must be interpreted as the sum of all the components $\{i, j, k, l\}$.
Finally, the wooden density was assumed to be $390\,kg/m^3$, and the safety factor was evaluated as $FoS = 2$, to be applied to the Tsai-Wu index.

2.2. Blade design

The objective of the blade structural analysis is to obtain a wooden design capable of withstanding loads under the most critical operating condition. According to the technical report of the IEA 3.4 MW turbine, the rated condition corresponds to the maximum structural load. At rated conditions, the rotor speed reaches its maximum value and pitch regulation begins, resulting in the maximum thrust force.
The most relevant rated parameters are: wind speed $U_{rat} = 9.8\,m/s$, rotor speed $\omega_{rot} = 11.75\,rpm$, and aerodynamic power $P_{rat} = 3.6\,MW$.
The blade structural design was therefore evaluated at rated conditions, considering the blade positioned at 90° clockwise from the vertical (positive upward direction), which represents the most critical configuration during a full rotation.
The criterion to compute a proper design is based on the maximum Tsai-Wu index in each section. Here in figure 2 the strategy to compute the local index is explained.

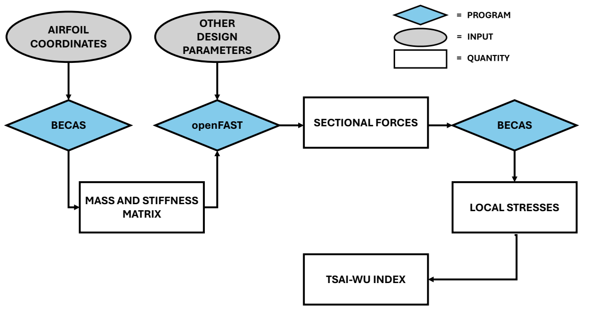

Figure 2: Flowchart of the blade structural analysis.

For this purpose, BECAS and OpenFAST were used. The first is a code developed by DTU (based on the theoretical issues explained in [1]) capable of carry out 2D FEM simulations: in this work it is twice used, first to compute the mass and stiffness properties of the cross section, and then to calculate the local stresses. In order to do that it is necessary to know the sectional loads, that are computed via OpenFAST, a BEM code that provides the aero-elastic (and beam) simulation of the blade (an already implemented OpenFAST model of the IEA 3.4 MW is available at [11]).
The blade design was obtained through an iterative procedure based on the maximum Tsai-Wu index evaluated in each cross section. The algorithm shown in Figure 2 was repeated until the target safety factor was achieved in each section. At every iteration, the thickness of the blade shell, spars, and shear webs was adjusted. However, achieving the target safety factor was not possible in all sections. In some regions, the loads were excessively high and the structural thickness had already reached the maximum allowable value.

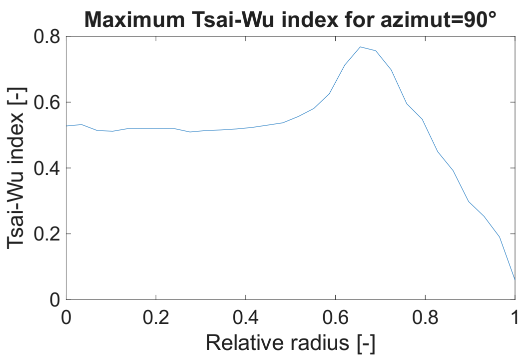

Figure 3: Tsai-Wu index along the blade in the worst condition.

To obtain better Tsai-Wu index values, the maximum allowable rotor speed was limited to $9.5\,rpm$ (note that figure 3 is referred to that rotor speed). The wind speed used for the design corresponds to the rated velocity of the reference turbine. Due to the rotor speed limitation, the aerodynamical rated power of the wooden configuration slightly decreases to $P_{rat,wood} = 3.0\,MW$.

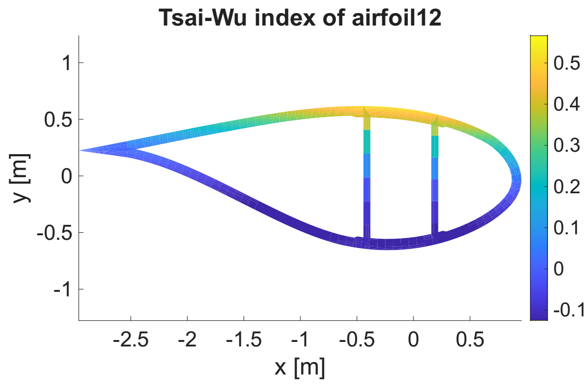

Figure 4: Sample sectional plot of Tsai-Wu index.

Here in the previous figure 4 there is an example of the sectional Tsai-Wu plot of an airfoil located at around $23.5m$ from the blade root.
The final weight of the wooden blade results 17.68 tons, against the 16.44 tons of the reference turbine.

2.3. Tower design

The tower structural analysis followed an approach similar to that used for the blade. However, the primary design constraint was not material failure but structural stiffness. Excessive tower-top oscillations emerged as the most critical issue.
The design objective was to achieve a tower-top deflection comparable to that of the reference turbine under identical loading conditions. The resulting wooden tower exhibits a top deflection of $\Delta x = 0.37\,m$, compared to $\Delta x = 0.35\,m$ for the reference turbine in respective rated condition.
To achieve the required stiffness, both the wall thickness and the external diameter were increased. The final wooden tower mass is 302 tons, against the 553 tons of the reference turbine. The iterative design process was simpler than for the blade, since only sectional stiffness

and mass properties computed via BECAS were required.

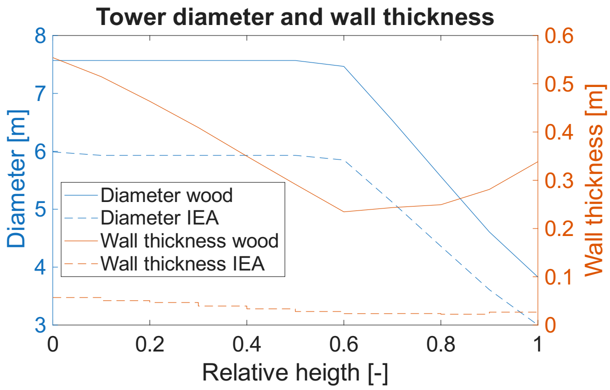

Figure 5: Tower diameter and wall thickness tor wooden and reference turbine.

Nevertheless, the tower design results described above can be derived from the evaluation of steady loads, which mainly consist of aerodynamic loads and the nacelle weight.
The rotor forces and moments were obtained from the blade structural analysis through an OpenFAST simulation. The dominant load components are the thrust force, equal to $478\,kN$, and the rotor torque, equal to $3.26\,MNm$. Forces and moments in the other directions were neglected, as they are oscillatory with zero mean value.
In addition, the nacelle contributes with its gravitational load and an eccentric load that generates a bending moment at the tower top. Finally, the self-weight of the tower was included, so that each cross-section is subjected to the weight of the entire portion of tower located above it.

3. Rotor performance and control

The performance of the machine was computed via FASTTool, that is a MatLab interface of the same code used in OpenFAST, that allows an easier access to the stationary performance and to the dynamic control of the machine.
First, the rotor power coefficient (C_p) was investigated for different pitch angles (β) and tip speed ratio (λ). The resulting surface can be represented via a level surface as in figure 6.

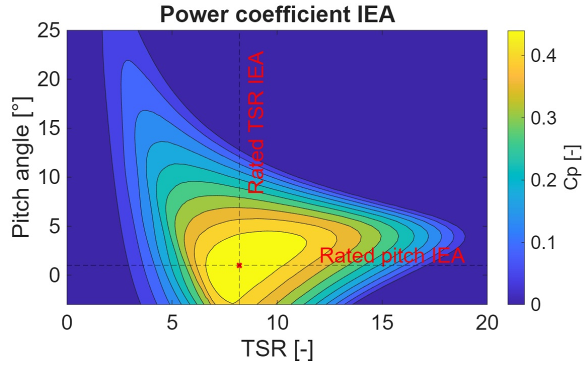

Figure 6: Power coefficient in function of β and λ.

As expected, the maximum value of C_p is located very close to the rated λ and β of the reference turbine, which are $\lambda = 8.16$ and $\beta = 0.87°$. Therefore, the goal is to keep the wooden turbine in that condition as much as possible when the wind speed changes. Actually, due to the discretization used, the value used for the following analysis are $\lambda = 8.2$ and $\beta = 1°$.

3.1. Power curve

The control strategy of the wooden turbine differs slightly from that of the reference turbine due to the lower allowable maximum rotor speed. In the IEA 3.4 MW configuration, torque control maintains optimal C_p operation below rated wind speed. Once rated conditions are reached, pitch control keeps both rotor speed and power constant.
In the wooden turbine, optimal C_p operation is maintained up to a lower wind speed because the rotor reaches its maximum allowable speed earlier. Between this point and the rated condition, rotor speed is kept constant while power continues to increase until rated power is reached, after which pitch control becomes active.
The turbine operates between a cut-in wind speed of $3\,m/s$ and a cut-out wind speed of $25\,m/s$.
The respective power curves are compared in figure 7, where R and M stands for the rated point and the point in which the wooden turbine reaches the maximum rotor speed.

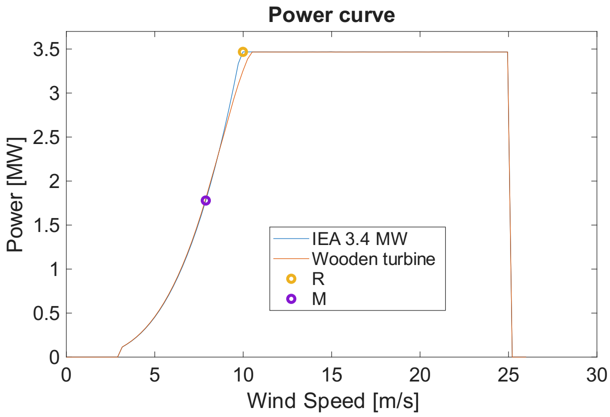

Figure 7: Comparison between wooden and reference turbine power curve.

3.2. Dynamic control

The dynamic response of the wooden turbine to torque and pitch control inputs is slightly slower than that of the reference turbine, mainly due to the higher blade mass. Nevertheless, the difference remains acceptable and does not significantly compromise control performance.
In figure 8 the response in terms of generator torque to a stepped wind from $10\,m/s$ to $12\,m/s$ is shown, that is representative of the response to the pitch control. The torque control show a very similar behavior.

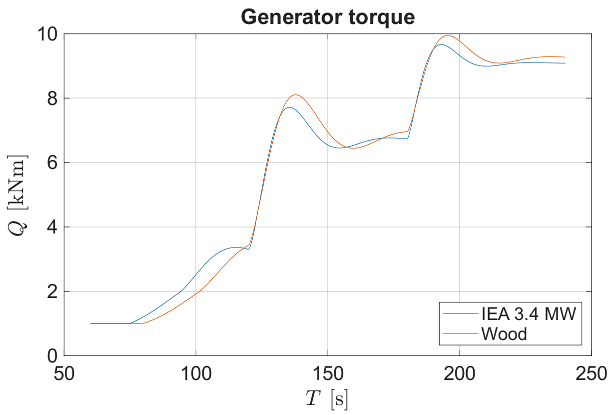

Figure 8: Response to a stepped wind with pitch control active.

4. Techno-economical analysis

The final part of the study consists of a techno-economic analysis aimed at evaluating the economic viability of the wooden solution under different wind conditions and installation scenarios (onshore and offshore). Three representative sites are considered. Cost estimation is based on NREL models ([9], [10]), and the Levelized Cost of Energy (LCOE) is finally calculated.

4.1. Wind resource and AEP

The three sites chosen for the analysis are in a mountain environment, near the italian city of Sondrio (site 1), offshore in Sardinia, near the city of Cagliari (site 2) and in the north sea (site 3), near the southern costs of Norway. The wind availability of these sites was evaluated via the probability density function (PDF), that for wind application is typically the Weibull function, whose expression is:

$$PDF_w(u) = \frac{k}{u} \cdot \left(\frac{u}{A}\right)^k \cdot exp\left[-\left(\frac{u}{A}\right)^k\right] \tag{2}$$

The coefficients A and k are available on the European Wind Atlas ([8]), so the PDF is known for each site. The resulting curves are shown in figure 9 with each respective mean wind speed.

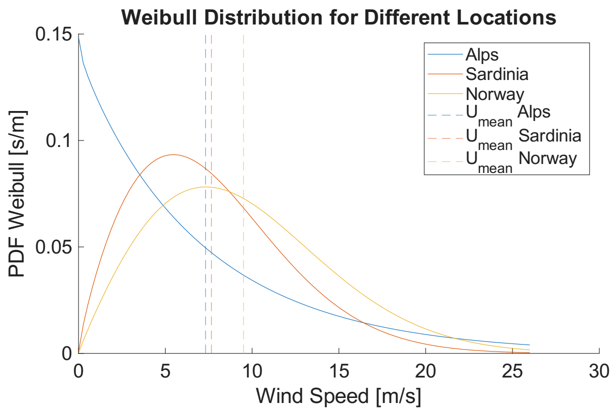

Figure 9: Weibull distribution for the chosen sites.

With the PDFs and the power curves showed in figure 7 it is possible to calculate the annual energy production (AEP) with the equation 3.

$$AEP = T\int_{U_{cutin}}^{U_{cutout}} P(u)PDF(u)du \tag{3}$$

The AEP resulting for each site both for reference and wooden turbine is reported in the following table.

	Site 1	Site 2	Site 3
IEA 3.4 MW $[GWh/y]$	10.325	14.363	18.351
Wooden $[GWh/y]$	10.228	14.279	18.250

Table 3: AEP.

As expected, the AEP of the wooden turbine is not way different from the reference turbine one, because the power curve is almost identical.

4.2. Cost estimation

The fixed costs were divided into blade, tower, nacelle and rotor auxiliaries, and support (foundation, platform, logistic and so on) costs, while the variable costs are the lease of land or sea, the operation and mantainance (O&M) and the levelized replacement costs (LRC). Note that the cost of the components (blade, tower and nacelle & aux) is increased of a marinization factor ($k_m = 1.135$) to take into account the higher resistance needed to the extreme environmental conditions.
The fixed costs of the reference a turbine were estimated through empirical correlation provided by NREL, while the wooden turbine fixed costs are assumed to be the same except for the tower and the blades cost, and, to a lesser degree, the transport and installation costs.
Concerning the variable costs, they are proportional to the AEP (lease and O&M) and to the rated power, but with different proportional laws between onsshore and offshore.
Here there are two tables summarizing the fixed and variable costs.

Item	IEA on.	IEA off.	Wood on.	Wood off.
Blade [k€]	390.10	442.77	300.90	341.52
Nacelle & aux [k€]	1610.16	1827.53	1610.16	1827.53
Tower [k€]	700.00	794.50	470.68	534.22
Support [k€]	1001.57	2422.60	906.92	2375.52
Total [k€]	**3701.84**	**5487.40**	**3288.66**	**5078.79**

Table 4: Summary of fixed costs.

Item	Site 1 IEA	Site 1 Wood	Site 2 IEA	Site 2 Wood	Site 3 IEA	Site 3 Wood
LRC [k€]	30.70	30.70	48.78	48.78	48.78	48.78
Lease [k€]	9.41	9.32	13.09	13.01	16.72	16.63
O&M [k€]	60.99	60.42	242.41	241.00	309.72	308.02
Total [k€]	**101.10**	**100.44**	**304.28**	**302.79**	**375.22**	**373.43**

Table 5: Summary of variable annual costs.

4.3. LCOE

Finally, the LCOE was calculated as:

$$LCOE = \frac{C_{fix} \cdot CRF + C_{var}}{AEP} \tag{4}$$

Where C_{fix} are the fixed cost, C_{var} the variable annual costs and CRF is the capital recovery factor, whose equation is 5, calculated assuming an interest rate i of 8%.

$$CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1} \tag{5}$$

The LCOE is strongly dependent from N, that is the life time in years. Since a durability analysis on the wood turbine is too complex to be carried out, two assumptions of life time were done: 20 and 16 years, that are respectively the same lifetime of the reference turbine (Voodin Blade Technology affirms that wooden components are as durable as traditional ones in [3]) and a more pessimistic scenario with a 20% shorter life time. The results are reported in table 6 and 7.

	Site 1	Site 2	Site 3
IEA 3.4 MW [€$/kWh$]	0.0463	0.0601	0.0509
Wooden turbine [€$/kWh$]	0.0461	0.0614	0.0519
Difference [%]	0.35	-2.15	-1.96

Table 6: LCOE for wooden turbine life time of 16 years.

	Site 1	Site 2	Site 3
IEA 3.4 MW [€/kWh]	0.0463	0.0601	0.0509
Wooden turbine [€/kWh]	0.0426	0.0574	0.0488
Difference [%]	8.08	4.44	4.12

Table 7: LCOE for wooden turbine life time of 20 years.

5. Conclusions

The main conclusions of this thesis can be summarized as follows:

- The blade structural analysis highlights significant criticalities. The target safety factor is not achieved in all blade sections, and fatigue loads were neglected in the present study. Therefore, a spruce blade with the same external geometry as the reference turbine is not structurally feasible without either modifying the geometry or introducing hybrid solutions with stronger materials.
- The tower appears considerably more suitable for wooden construction. Tower-top deflection can be maintained at values comparable to the reference turbine, and material failure remains well below the imposed safety factor.
- Rotor performance and control strategies are not significantly affected by the use of wood and do not represent a major technical challenge.
- From an economic perspective, the results are strongly dependent on the assumed lifetime. Under equal lifetime assumptions, the wooden solution can be competitive, particularly for onshore applications where tower and blade costs account for a larger fraction of the total investment.

References

[1] Stolpe M. Blasques J.P. Multi-material topology optimization of laminated composite beam cross sections. *Composite Structures*, 2012.

[2] Pietro Bortolotti, Helena Canet Tarres, Katherine Dykes, Karl Merz, Latha Sethuraman, David Verelst, and Frederik Zahle. Iea wind task 37 on systems engineering in wind energy – wp2.1 reference wind turbines. Technical report, International Energy Agency, 2019.

[3] https://voodin-blades.com/.

[4] Kristian Dahl. *Mechanical properties of clear wood from Norway spruce*. PhD thesis, NTNU, 2009.

[5] https://github.com/IEAWindSystems/IEA-3.4-130-RWT/tree/master/xlsx.

[6] Marek Johanides, David Mikolasek, Antonin Lokaj, Petr Mynarcik, Zuzana Marcalikova, and Oldrich Sucharda. Rotational stiffness and carrying capacity of timber frame corners with dowel type connections. *Materials*, 14(23), 2021.

[7] David E. Kretschmann. *Wood as an engineering material. Chapter 5: Wood mechanical properties*. Forest Products Laboratory, 2010.

[8] https://map.neweuropeanwindatlas.eu/.

[9] https://docs.nrel.gov/docs/fy07osti/40566.pdf.

[10] https://docs.nrel.gov/docs/fy19osti/73585.pdf.

[11] https://github.com/IEAWindSystems/IEA-3.4-130-RWT/tree/master/openfast.