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Topology Optimization of a Jacket Structure for an Offshore Wind Turbine with a Genetic Algorithm

Johan Henrik Martens[1,2], Daniel Zwick[3], Michael Muskulus[4]

[1] Norconsult AS, Oslo, Norway, johan.henrik.martens@norconsult.com
[2] Norwegian University of Science and Technology, NTNU, Trondheim, Norway
[3] Norwegian University of Science and Technology, NTNU, Trondheim, Norway, daniel.zwick@ntnu.no
[4] Norwegian University of Science and Technology, NTNU, Trondheim, Norway, michael.muskulus@ntnu.no

1. Abstract

Structural optimization of support structures for wind turbines is complicated by the need to assess fatigue damage. Due to nonlinearities in the rotor loads, this situation calls for transient time-domain simulations, with combined wind and wave action. The structural model considered here is a jacket consisting only of beam elements that is subject to one 90 second operational loadcase from which the fatigue constraint is evaluated. Since no optimality theory exists for such a case, the optimization was performed with a genetic algorithm using a small population of designs. Under a ground structure approach, the structure was initially modeled with a large set of beams. By storing favorable design traits and discarding bad traits, the beams were sized in an iterative manner. Beams under a certain minimum size were removed. The objective function includes a term for the cost of welding and painting the beams, and thereby favors less structural elements. Results show that it is possible to obtain reasonable structures with this approach, similar to what would be obtained by straightforward manual optimization, but often with a lower weight. Due to the many simplifications the final designs are not completely realistic, but this study highlights the important issues that do arise and is a first step toward more comprehensive automatic design optimization.

2. Keywords: Wind Turbine, Jacket, Optimization, Genetic Algorithm

3. Introduction

The construction of offshore wind farms for electricity production has shown great promise. Both as a contributing element in mitigating the ongoing climate changes, and in lessening the global oil dependency. Wind power is in terms of cost of energy the second cheapest of all renewable energy sources, after hydro-power. Still, construction and operation cost is a limiting factor in utilization of offshore wind energy on a significant scale. For an onshore installation, the cost of the turbine and tower itself will typically be 64-84% of total capital costs, while for offshore wind farms it will only make up 30-50% [1]. To realize cost efficient offshore wind farms, minimization of the support structure cost is essential. For water depths between 30 and 60 m, tubular steel lattice towers, i.e. jackets, are a favored solution. Environmental factors that need consideration when designing offshore wind turbines include high wind speeds, turbulence, wave loading, ice, currents, tides, marine growth and corrosion [2]. Not only are all these factors hard to predict and design for individually, but their coupled effects are also important to consider.

Structural optimization is a design scheme for finding optimal solutions. The goal of the process is structures that are stiff, economical and easily producible while satisfying mechanical constraints like displacements, stress levels, fatigue damage, buckling and eigenfrequencies. Several methods can be employed to arrive at an optimized design. However, most existing methods are based on maximizing stiffness, using one or more static loadcases, whereas the problem here has to take fatigue constraints into account. This is difficult with gradient-based algorithms [3], especially for a system that is subject to such a complex dynamics as a wind turbine. The current state of the art of support structure optimization is therefore the use of heuristics [4, 5].

One such method is the genetic algorithm (GA), which mimics the evolutionary process known as ”survival of the fittest”. By continuously passing on good design traits and discarding unfavorable traits, the design will improve over generations. Evolutionary optimization schemes are powerful because they can find innovative solutions to complex problems in an enormous search space. The solution adapts to changing environments and one can easily take advantage of parallel processing. Compared to more traditional, gradient-based, optimization methods it is also relatively straightforward to implement. Weaknesses of GA are among others difficulties relating to premature convergence of the solution and in defining a suitable fitness function, which defines the goal of the optimization process.

4. Methodology

The optimization process is based on an interaction between Fedem Windpower (Ver. R7.1-α2, Fedem Technology AS, Trondheim) and a MATLAB script. Fedem Windpower is a flexible multibody software specialized in dynamic simulation of wind turbine systems. It offers tools for designing realistic rotors and support structures, and for modeling wind and sea conditions. The topology is optimized by reducing the task to an equivalent sizing problem of a ground structure of varying complexity. The ground structure includes all possible beam connections between predefined nodes in the jacket. The inner and outer diameter of the beams are sized by the script and beams that have a diameter which is smaller than a certain limit will be removed. To limit the size of the search space, a maximum outer diameter, as well as upper and lower bounds for the ratio between the inner and outer diameter are inputs to the optimization script.

As the goal of this research is to optimize a jacket structure, an existing model of the transition piece, tower and rotor nacelle assembly (RNA) was utilized. Namely, a model from the OC4 project [6], illustrated in Fig. 1. Data about the wind and sea conditions the wind turbine was subjected to during analysis were gathered from a reference site in the Dutch North Sea [7]. The wind file was generated by TurbSim, a tool developed by NREL (National Renewable Energy Laboratory, Boulder). Wave loading was applied using a JONSWAP sea wave spectrum. Total analysis time was set at 90 seconds and data was recorded in every time step (size 0.05 s) of the last 30 seconds of the analysis. The first 60 seconds are devoted to accelerating the turbine, i.e., to reach steady state conditions. An overview of the entire design optimization process utilized is illustrated in the flowchart in Fig. 2.

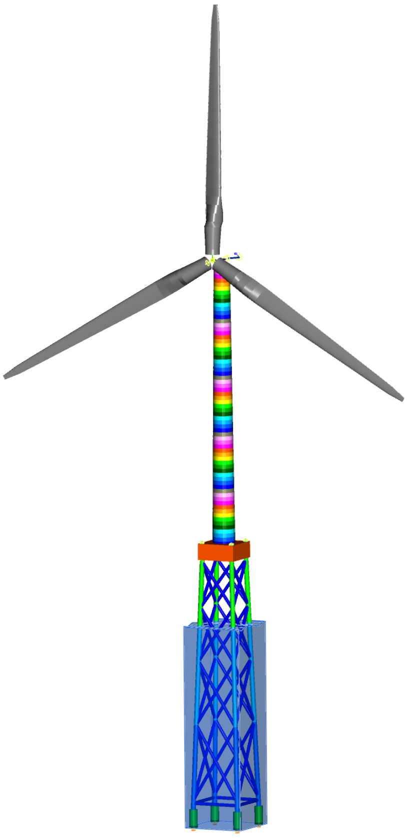


Figure 1: Wind turbine model from the OC4 project

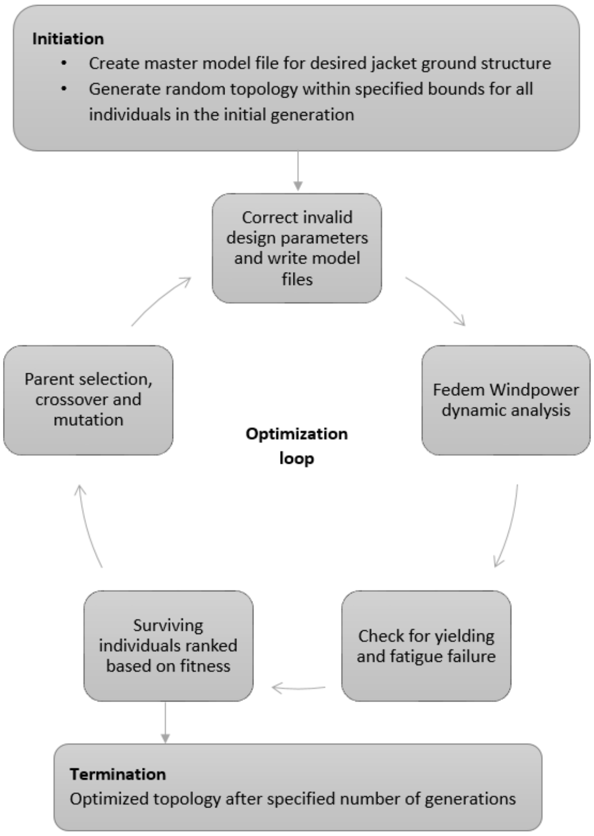


Figure 2: Flowchart of optimization process

The genetic algorithm was carried out by a MATLAB-script. The first generation of jackets were generated with a random topology, the only limitations being the ground structure definition and the diameter bounds. The script also ensured that all four faces of the jacket were symmetric. Fedem input-files were written for all individuals, i.e. jackets, in the generation and were analyzed in parallel. Data exported from Fedem were axial force and moment about the Y and Z axis for both ends of all active beams in the model. The forces were converted to a stress time series which was checked for yielding and fatigue failure. Working by the DNV guidelines [8], all beams were evaluated for fatigue damage in eight hot spots at both ends. Extraction of stress ranges from the stress time series was done by rainflow counting following standard procedure [9]. The 30 second loadcase from the analysis was scaled in order to predict fatigue damage through a 20 year lifespan.

After testing the yield criterion and the fatigue limit state, all surviving individuals were evaluated for fitness. Casualties, either by fatigue, yielding or by the Fedem solver module crashing, were discarded. Fitness was calculated as an arbitrary constant minus the objective function. The objective function to be minimized represents a rough estimate of the total cost of the jacket and includes both a fixed cost per member, as well as material cost. This ensures that jackets with less members are favored by the algorithm. In order to track the evolution and determine which individuals will pass on their genome to the next generation, a leader table/mating pool is updated and stored for each generation. The number of individuals in the mating pool equalled the population size. For all generations except the first, the result of the current generation was added to the mating pool. This list was then sorted from best to worst fitness, mixing new results with the old leaders. Hence, an individual in the mating pool will not leave the mating pool unless replaced by an individual with better fitness. Next, individuals in the mating pool bred children for the following generation. Two parent individuals were selected by means of a weighted roulette wheel, ensuring that individuals with the highest fitness have the highest probability of being chosen as parents. All inner and outer beam diameters in a parent, i.e. chromosomes, were converted to binary numbers where each bit represents a gene. A crossover was performed by mixing chunks of genes from both parents in each child chromosome. A mutation was implemented by randomly switching genes from 1 to 0 and vice versa. The probability of such a mutation adapts to the diversity in the mating pool in an effort to avoid premature convergence. A low diversity among the leading designs calls for a higher mutation probability. The diameters of the beams in the children were checked to be inside the user-specified bounds and new Fedem input-files were written. This iterative optimization loop was carried out for a specified number of generations. The winning design is the individual with the highest fitness upon termination. More details can be found in [10].

5. Results

In the following, examples of two optimization runs are presented. First, an unrealistically low cubic jacket with 3 nodes along its width, i.e. nodes in all corner legs and one additional node in between, was optimized. Second, a more realistic 32 m tall jacket with 2 nodes along its width, i.e. only nodes along the four legs, was analysed. Satisfactory results with a 32 m tall jacket with 3 nodes along its width could not be obtained with the available processing power. Having 2 nodes along its width implies that X-braces are not connected, i.e. welded together, at the their intersection.

5.1. Optimization of a cubic jacket

Figure 3 shows a plot of the evolution throughout the optimization process. The plot shows the fitness on the left abscissa, and the generation number on the ordinate. The maximum fitness is 50, which would correspond to a structural cost of 0. The optimization was set to run for 50 generations and each generation had a population of 16 individuals. The thick blue line indicates the fitness of the best design so far in the optimization process, while the thin green line shows the fitness of the best individual in each generation. The dotted line illustrates the mean fitness in the mating pool. If the distance between the mating pool mean and the leading design is small, the diversity in the mating pool is low.

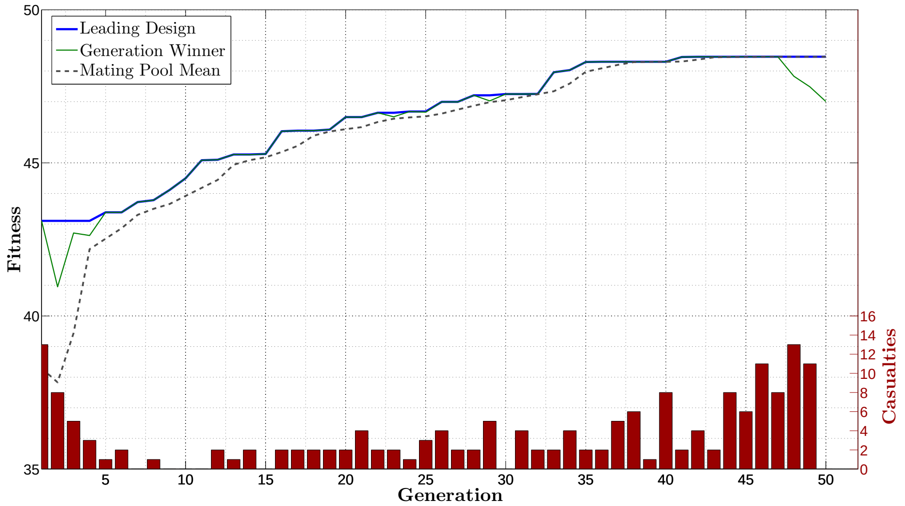
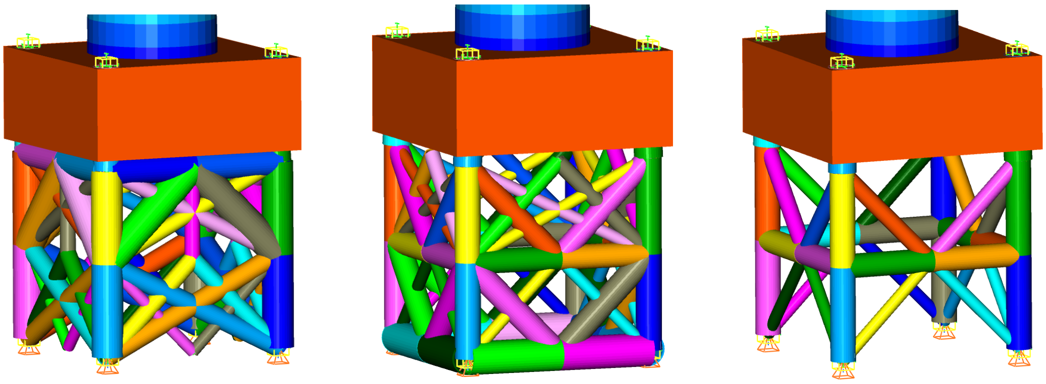


Figure 3: Optimization of a cubic jacket

As one would expect, the diversity is high in the initial generations and lower as the design converges towards a solution. The red bars with the corresponding right abscissa illustrate the number of casualties, i.e. failures, within each generation. The effect of the adaptive mutation probability can be seen at the very end of the optimization evolution. As the diversity in the mating pool decreases, the mutation probability increases, as illustrated by lower fitness of the generation winners and more casualties.

Fig. 4a illustrates a random topology from the initial generation. By the 15th generation, Fig. 4b, the structure is lighter and somewhat more purposefully designed. The winning design is produced in the 46th generation, as seen in Fig. 4c. Its fitness increased from 43.1 in the initial generation to 48.5 in the 46th generation. A classic X-brace has been formed in parallel with a horizontal support. The small dimensions of the X-brace have probably made the horizontal support mandatory in controlling wave induced oscillations of the braces. Although the topology of the winning design can be found within the leading design of generation 15, there are many other possibilities that have been discarded in the optimization process.



(a) Initial random design (b) Leading design, 15th generation (c) Winning design, 46th generation

Figure 4: Cubic jacket at different optimization stages

5.2. Optimization of a tall jacket

The jacket with two nodes along its width was optimized over 100 generations with 16 individuals in each generation. The maximum fitness in this example is 100. The entire optimization took roughly 24 hours in a completely automatic process on a regular workstation, and was subdivided into 12 hours of Fedem analyses, 10 hours of stress and fatigue analyses and 2 hours of writing model files. As seen in Fig. 5, most of the increase in fitness is done before the 25th generation. The second half of the optimization, from generation 50 to 100, displays traits of many bad designs through the fluctuating fitness of the generation winners and a high number of casualties.

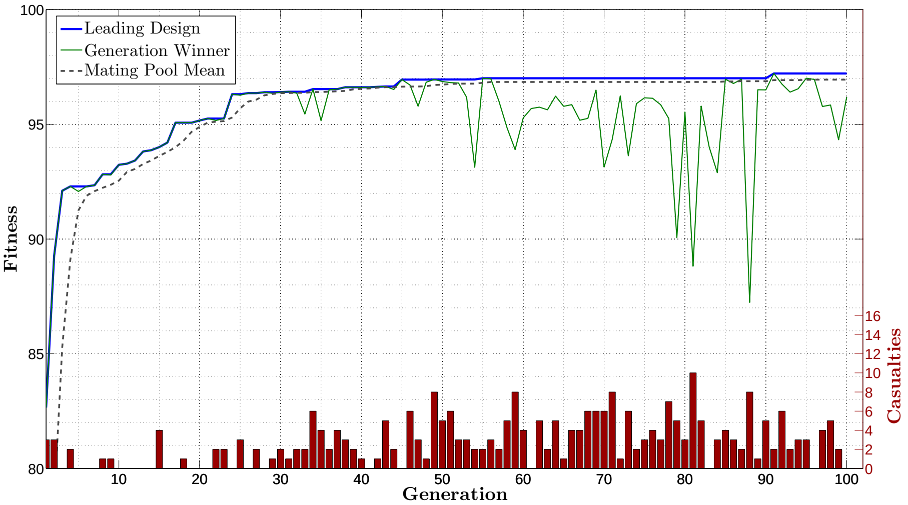
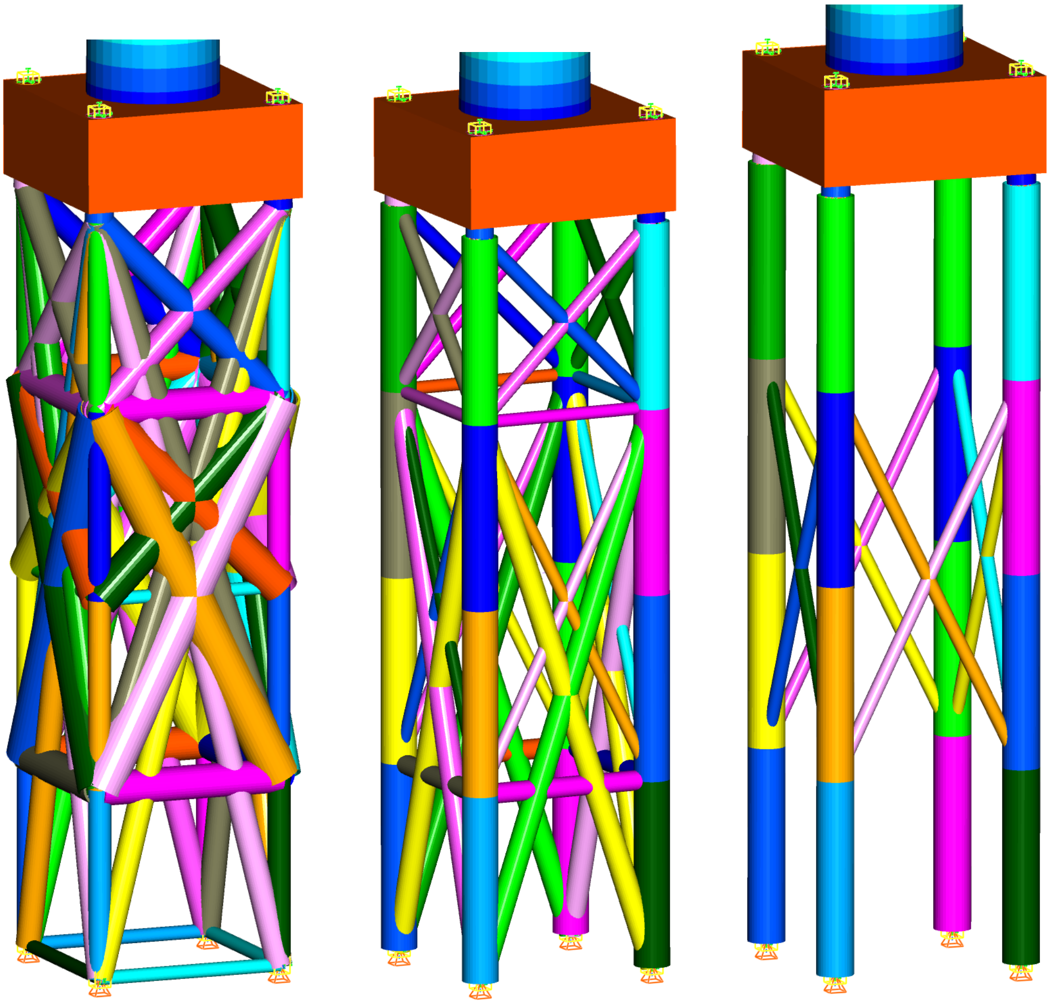


Figure 5: Optimization of a tall jacket

The evolution of the topology is illustrated in Fig. 6a-6c and exhibits how structural cost is being minimized by the optimization script. A lot of the initial weight has been cut already by the 5th generation, as shown in Fig. 6b. From generation 5 and onwards the only non-sizing changes are the removal of two horizontal beams and two X-braces on each face. The winning design in Fig. 6c looks inexpensive and reasonable for the given loading, which was the goal of the objective function. It has a thin stabilizing X-brace in the middle of each face and large legs with an outer diameter of 1.537 m and a thickness of 25 mm. It is impressive that the single brace formed exactly halfway up the jacket, where there is need for support, considering that there is no enforced symmetry about the horizontal middle line. However, the design seems prone to buckling failure, which was not evaluated by the script.



(a) Initial random design

(b) Leading design, 5th generation

(c) Winning design, 91th generation

Figure 6: Tall jacket at different optimization stages

5.3. Comparison with manual optimization

In order to have a basis of comparison for the automatically optimized designs, a simple manual optimization was carried out. A classic topology with one X-brace on each face as well as four legs was assumed as the optimal design for the cubic jacket. The tall jacket was modeled with four such X-braces throughout its height as a basis for the manual optimization. The initial cross sections of the legs and braces were set equal to the inner and outer diameters of the legs and braces from the jacket model used in the OC4 project [11].

To minimize the cost of the structure manually, the outer diameter was kept constant while a sizing optimization was carried out for the inner diameters. In other words, the manual optimization process had two design variables, the inner diameter of the braces and the inner diameter of the legs. The jacket was subjected to the same loading and stress assessment as with the automatic optimization. If a brace or leg failed, either by yielding or fatigue, the inner diameter was decreased and vice versa if no failures occurred. This iterative process was carried out until an increase of 1 cm of the inner diameter of either the legs or the braces would cause a failure. To compare this result with the jackets that were optimized by GA, the fitness score of the manually optimized jacket was calculated by

Table 1: Comparison of automatic and manual optimization process

	Maximum fitness	Automatic	Manual
Cubic jacket	50	48.4658	47.9314
Tall jacket	100	97.2175	97.7768

the same rules as in the automatic optimizations. The automatic optimization was superior for a cubic jacket, but not for the tall jacket. Fitness results are given in Table 1.

6. Conclusion

The jacket topologies generated by means of evolutionary optimization showed a complexity-dependent quality. The automatic optimization of a simple cubic jacket beat the quick manual optimization of the same ground structure. The taller and more complex jacket topology had a marginally better fitness by manual optimization.
The employed optimization process is by no means without fault and there is much room for improvement. Some of the weaknesses of the implementation include that no ultimate limit state load case was checked, buckling of members was not assessed and the ground structure did not allow for inclined legs. Still, important aspects regarding the use of evolutionary optimization on a jacket have been explored. The results have shown that structural cost can be minimized in a reasonable manner under fatigue constraints using genetic algorithms. Reasonable and innovative designs were generated in a very large search space of possible solutions. The method shows great promise because it is powerful and at the same time easy to implement. If a more general ground structure were to be optimized on a supercomputer by use of a combination of GA and manual optimization, it is likely that more cost-efficient designs could be constructed.

7. References

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