Energies **2013**, *6*, 3822-3840; doi:10.3390/en6083822

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

A Virtual Tool for Minimum Cost Design of a Wind Turbine Tower with Ring Stiffeners

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Received: 8 May 2013; in revised form: 22 June 2013 / Accepted: 2 July 2013 / Published: 29 July 2013

Abstract: Currently, renewable energy resources are becoming more important to reduce greenhouse gas emissions and increase energy efficiency. Researchers have focused on all components of wind turbines to increase reliability and minimize cost. In this paper, a procedure including a cost analysis method and a particle swarm optimization algorithm has been presented to efficiently design low cost steel wind turbine towers. A virtual tool is developed in MATLAB for the cost optimization of wind turbine steel towers with ring stiffeners using a particle swarm optimization algorithm. A wind turbine tower optimization problem in the literature is solved using the developed computer program. In the optimization procedure the optimization results match very well with the optimization results obtained previously. The wall thickness of the shell segments and the dimensions of the ring stiffeners are selected as the design variables, and the limits of the local buckling for the flat ring stiffeners, the local shell buckling limit, the panel ring buckling limit and the limitation of the frequency are considered the design constraints. Numerical examples are presented to understand the impacts of the design variables on the total cost of the wind turbine tower.

Keywords: wind turbine; steel tower; structural optimization design; cost minimization; virtual tool

1. Introduction

Recently, renewable energy resources are becoming more important to reduce greenhouse gas emissions and increase energy efficiency. The efficient use of renewable resources such as wind energy, solar thermal power generation, photovoltaics, geothermal power generation, and biomass power generation depends on the cost of clean energy technologies. Some clean energy technologies are relatively costly today, but costs may decrease over time as technological improvements occur, equipment is standardized, and the economies of scale take hold. If low-cost clean energy resources, such as wind energy, constitute a major portion of the portfolio of clean energy resources, the overall cost impact of reducing greenhouse gas emissions will be diminished, and efforts to curtail greenhouse gas emissions will be more politically and economically feasible [1–3].

Wind power, which is the fastest growing energy source, will play a vital role in the future energy supply of the world. Worldwide, wind energy will also supply a sizeable amount of electricity—approximately 16% in 2020, according to the forecasts of the Global Wind Energy Council [3]. The wind industry and governments have worked together for more than 20 years to advance both large and small wind energy technologies and to decrease the cost of energy. In spite of increasing capacities and reducing costs in large wind turbines, technological advances in wind turbines are still needed to bring the cost of wind energy to a level competitive with conventional generation sources. As reported in the literature, the initial cost of wind turbines is about half of the total wind plant development costs. Therefore, reducing the cost of wind turbines through advanced technology is one of the successful ways to decrease the cost of wind energy [4].

A wind turbine is a complex system in which design is a matter of constant tradeoff between the competing demands of lower cost, better energy productivity, increased lifetime, reliability and durability, and maintenance cost. Achieving a greater yield of the energy production may be costly without appropriate techniques. In this field, reducing materials to reduce capital investment may adversely affect operations and maintenance (O&M) costs. As a result, the technical concepts of modern wind turbines have to be significantly developed to create more lightweight and cost-effective designs.

The growth of wind power has led to an interest in addressing wind turbine towers. Negm and Maalawi [5] performed a structural optimization of a wind turbine tower. They proposed a simplified method that used structural analysis instead of the traditional finite element method (FEM) approach. Lavassas *et al.* [6] studied the static and dynamic behaviour of a 1 MW wind turbine tower using both detailed and simplified finite element models. They found that the seismic response was significantly less critical than the response caused by wind loading. Bazeos *et al.* [7] performed a stability analysis on a steel wind turbine tower and concluded that seismic analysis does not produce the governing design criterion for this type of structure. In recent years, the development of optimization algorithms has supplied designers with interesting tools to design wind turbine towers. Uys *et al.* [8] developed a procedure to achieve a design that will minimize the cost of a slightly conical steel tower for a wind turbine. This procedure was applied to the 1 MW steel wind turbine tower proposed by Lavassas *et al.* [6]. Silva *et al.* [9] developed a non-linear dynamic model based on experimental data for the structural analysis of reinforced concrete towers. This model was used to formulate some optimization problems to minimize the cost of reinforced concrete wind turbine towers. Wind turbine towers with different heights were analyzed to find the best solution by considering the cost, reliability and computational time. In this study, a computer program was developed to minimize the cost of a wind turbine steel tower with ring stiffening. This computer program uses the reliable procedure proposed in [10–15] and is based on Det Norske Veritas' rules [16] and practice rules to optimize the design of a ring stiffened cylindrical shell loaded in bending and improve the particle swarm optimization algorithm. The optimization results obtained are presented and discussed.

To obtain cost-effective wind turbines, reducing the tower head weight, including the gearbox, rotor and blades, as well as the tower weight is very important. Because larger towers generally require larger transport vehicles and cranes, reducing the weight can decrease transportation and installation costs. Installation costs include those associated with transportation, construction, and interconnection. New tower technologies and materials, such as self-erecting towers and lightweight materials, have the potential to decrease installation costs. Currently, tubular steel towers have been used in wind turbines because they are more reliable. Therefore, designers need to find optimum designs for tubular steel towers by mainly taking into account the rated torque and maximum wind speeds. Computer tools based on reliable optimization algorithms may help designers design wind turbine towers and understand the effects of design parameters such as the hub height, the tower diameter and the wall thickness. In this paper, a virtual tool is developed to minimize the tower weight and the welding cost of a tubular steel tower. This tool is based on particle swarm optimization algorithm and is written in MATLAB. This code also allows the influence of some design parameters on the tower weight to be investigated.

2. Particle Swarm Optimization (PSO)

Because evolutionary algorithms such as genetic algorithms and evolutionary programming do not need to apply mathematical assumptions to the optimization problems and have better global search abilities when compared with conventional optimization algorithms, they have gained importance in structural and mechanical optimization problems in recent years [17–26]. Currently, a new evolutionary computation technique, called particle swarm optimization (PSO), has been successfully applied to structural and mechanical optimization problems.

PSO was inspired by the social behavior of biological organisms, especially the ability of the groups of some species of animals to work as a whole in locating desirable positions in a given area, e.g., birds flocking to a food source. In PSO, such social behavior is modeled as an optimization algorithm that guides a population of particles moving towards the most promising area of the search space. These particles are called the swarm. Unlike in the other evolutionary computation techniques, each particle in PSO is also associated with a velocity that is dynamically adjusted according to the historical behaviors of the particle. Hence, the particle's position is changed according to its own behavior and that of its neighbors. Therefore, the particles have a tendency to move towards a suitable search area over the course of the search process.

Particle Swarm Optimization for Constrained Engineering Design Problems

The particle swarm algorithm was first introduced by Eberhart and Kennedy [17]. The motivation behind the algorithm was the intelligent collective behavior of organisms in a swarm (e.g., a flock of migrating birds) because the behavior of a single organism in the swarm may be totally inefficient. PSO was first designed to simulate birds seeking food, which is defined as a "cornfield vector". Similar to other evolutionary algorithms, PSO can solve a variety of hard optimization problems but with a faster convergence rate [26]. Another advantage is that it requires only a few parameters to be tuned, making it attractive from an implementation viewpoint. Standard PSO is usually applied to solve unconstrained optimization problems. In this paper, the standard PSO algorithm is extended to solve constrained mechanical design optimization problems using methods that preserve a feasible population. PSO algorithms have also been applied to constrained optimization problems. For example, a bird finds food through social cooperation with other birds around it (within its neighborhood). PSO was then expanded to a multidimensional search. If the search space is *d* dimensional, the *ith* particle of the swarm can be represented by a *d* dimensional vector *x*. The velocity of this particle can be represesented by another *d* dimensional vector *v*. The original PSO algorithm is described below:

$$v_{id} = w\, v_{id} + c_1 R_1 (p_{best,i} - x_{id}) + c_2 R_2 (g_{best,i} - x_{id}) \tag{1}$$

$$x_{id} = x_{id} + v_{id} \tag{2}$$

where the index i represents the number of particles in the population and the index d represents the dimension of the solution; x_i and v_i are the current position and velocity of the *ith* particle, respectively; c_1 and c_2 are learning factors and are the social and cognitive components, respectively; and R_1 and R_2 are two random numbers between [0,1]; w is the inertial weight factor, and shows the effect of previous velocity vector on the new vector. Equation (1) calculates a new velocity (v_{i+1}) for each particle based on its previous velocity, the best location it has achieved (p_{best}) so far, and the global best location (g_{best}) the population has achieved. Equation (2) provides the particle's updated position in the search space.

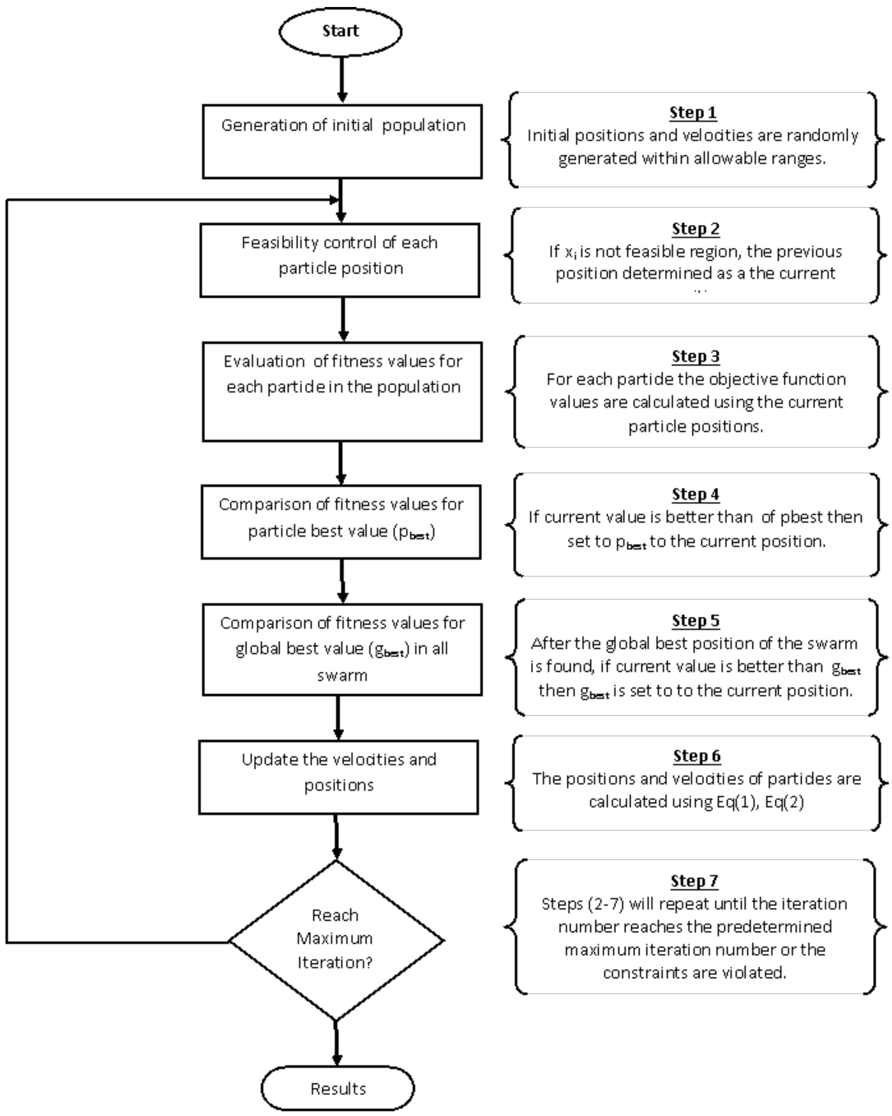
Many researchers have expanded on the original idea with alterations ranging from minor parameter adjustments to complete a reworking of the algorithm. Others have used PSO to compare other global optimization algorithms, including genetic algorithms and differential evolution.

In the last few decades, great attention has been paid to structural optimization because raw material consumption is one of the most important factors that influence building construction. Material cost increases are offset entirely by the reduction of the use of that material due to the material being stronger and therefore less of the material being required. Additionally, as structures become larger such as wind turbine tower, production, transportation and installation costs will also rise. Because of the increasing demand for high-performance and low-cost structures, designers prefer to minimize the volume or the weight of the structure by optimization.

Many researchers have been working to find a technique to maintain a feasible population. There are a number of techniques proposed to handle constrained optimization problems. One of them is a technique called "fly back mechanism" and is proposed by He *et al.* [26]. This technique maintains a feasible population by incorporating a well-known basic PSO algorithm for solving structural optimization problems. PSO algorithms based on this technique are more reliable when compared with other algorithms based on penalty functions. According to this technique, the particles are initialized in a feasible search space. When the particles fly in feasible space to search for the solution, if any particle passes into infeasible space, it returns to a previous feasible position by flying back. Thus, a solution in feasible space will be guaranteed. Because the particle is most likely close to the boundary, the particle swarm optimization algorithm, improved by using a fly-back mechanism, has the important advantage of finding the global minimum faster than other algorithms for constrained structural optimization problems.

According to He *et al.* [26], regarding the proposed constraint handling technique, the improved particle swarm optimization with fly-back mechanism requires a feasible initial population to guarantee that the solution of successive generations are feasible. To generate a feasible initial population, an extra loop at the beginning of the algorithm is required to keep randomly re-initializing infeasible particles to ensure that they stay inside the feasible search space. General experience indicates that this is simple method is sufficiently good most mechanical and structural design problems since their feasible search spaces are usually large and feasible particles can be easily generated. Small size populations are preferred to minimize the time to find a feasible initial population. When examining all results presented in [26] it can be seen that the optimization results by the particle swarm optimization algorithm with fly-back mechanism are better or equal to other existing methods such as Genetic algorithm, Genetic search technique, Runarsson stochastic ranking method. However, a more important drawback of this technique is the requirement of an all-feasible initial population. This may be a disadvantage when dealing with problems with a very small feasible region. The "fly-back" mechanism keeps particles from flying out of the feasible region by discarding those flights which generate infeasible solutions. Since a large number of the particles' flying behaviors are wasted, due to searching outside the boundary in the complex structure optimization problem, iteration number may rise and time cost may increase. In this study, the particle swarm optimization algorithm with fly-back mechanism is used for the cost minimization of wind turbine towers. The particle swarm optimization algorithm can be described using the general flowchart given in Figure 1.

Figure 1. The flowchart of the particle swarm optimization.



3. The Optimal Design of a Wind Turbine Steel Tower

In a wind turbine, the tower that carries the rotor and the nacelle is one of the key components. Towers for large wind turbines may be either tubular steel towers, lattice towers, or concrete towers [9]. Approximately 90% of all wind turbine towers are tubular steel towers. They are called tapered tubular towers because they gradually narrow towards the top. Because a wind turbine tower supports the rotor, nacelle and power transmission and control systems in the nacelle, it increases the weight of the rotating blades. The tower affects the efficiency and reliability of the wind turbine. Therefore, it should be designed and manufactured taking into account constraints such as the strength, frequency, stability and weight. The weight of the tower in a wind turbine has to be minimized for easy transportation and assembly. Today, a minimum weight structural design is of utmost importance for the successful and economical operation of a wind turbine. The reduction in the weight of the tower is very beneficial because of the manufacturability and cost. Therefore, modern optimization algorithms may help in obtaining successful tower designs under many constraints.

In this study, the cost calculation procedure for a wind turbine tower proposed by [8] is used to conduct the structural optimization of a wind turbine tower. This procedure finds the minimum cost depending on constraints such as the local buckling of the flat ring stiffeners, local shell buckling, and panel ring buckling in the tubular steel structure of the wind turbine. The procedure is extended with a natural frequency constraint. There are four design variables, the height and thickness of a flat ring stiffener (h_r and t_r, respectively), the wall thickness (t) and the diameter (D). The constrained optimization problem of a steel wind turbine tower and the objective function and constraints are described below:

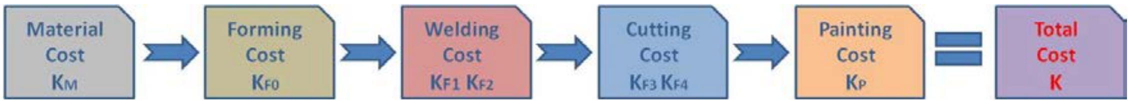
3.1. Objective Function to be Minimized

The cost estimation is important in structural design. Thus recent advances achieved in technology such as integrated engineering, provide a new concept in the cost estimation starting from the design phase. In a structural design, designers should consider many important variables such as loads, materials, geometry, fabrication, transport, installation, maintenance and costs. Designers need cost function to be mathematically formulated as a function of these variables. Farkas and Jarmai [12] developed a cost calculation method for various welded steel structures. The model performs a cost function based on knowledge in practice and considered manufacturing operations. The cost function includes the cost of material, cutting, forming, assembly, welding and painting. This cost function has been applied to minimum cost design problems of various steel structures such as welded beams, layered sandwich beams, tubular trusses, frames, stiffened plates and shells. The virtual tool developed in this study uses this cost function for minimum cost design of wind turbine towers constructed with welded shells. The cost function, namely, the objective function, including the cost of material, assembly, welding and painting, is formulated according to the manufacturing process as in Equation (3):

$$K(R,t) = K_M + 5(K_{F0} + K_{F1}) + K_{F2} + K_{F3} + K_{F4} + K_p \tag{3}$$

The total cost also includes the cost of forming shell elements from a flat plate into near cylindrical shapes, the cost of cutting the flat ring stiffeners as well as the cost of painting and welding (Figure 2). When five shell elements with a length of 3 m without rings are manufactured, two axial butt welds are needed for each shell element. To avoid shell ovalization the number of stiffeners is suggested between 5 and 15 in [10]. It is clear that the cost increases as the number of stiffeners increase in wind turbine tower. In this paper, the number of stiffeners is set to 5 as a constant. In [8] it was mentioned the cost difference for the variation in number of ring-stiffeners (5–15) was too small (1.5%–3.6%).

Figure 2. Cost function for the wind turbine tower.



The total material cost for each shell is:

$$K_M = k_M \rho V_2 \tag{4}$$

where k_M is the material cost factor and is taken as $k_M = 1$ \$/kg in this paper; ρ is density of the tower material and is 7.85×10^3 kg/m^3 for steel. The volume of material for a shell, V_2, is found by:

$$V_2 = 5V_1 + (D - h_r)\pi h_r t_r n \tag{5}$$

where t_r, h_r are the ring stiffener thickness, the ring stiffener height respectively; D is the elements of diameter to be welded; n is the number of elements to be assembled; V_1 is the volume of an element:

$$V_1 = D\pi t \cdot 3000 \tag{6}$$

The cost required to form a shell element into a slightly conical shape is considered in the factor K_{F0}, which is given by:

$$K_{F0} = k_F \theta_F T \tag{7}$$

where T is the time spent on bending a plate element 3 m wide for 4 mm $\leq t \leq$ 40 mm and 1750 mm $\leq D \leq$ 3500 mm and can be calculated by Equuation (5). This formulation was derived from real data obtained from industry by Farkas and Jarmai [10]. θ_F is the difficulty factor, including the difficulty of fabrication and $\theta_F = 3$ is used in this paper as proposed by Farkas *et al.* [12]. k_F is the labor cost factor for each unit time and $k_F = 1$ \$/min as proposed by Farkas [11]:

$$lnT = 6.85825 - 4.5272t^{-0.5} + 0.0095419D^{0.5} \tag{8}$$

In this equation, which also includes the time to form the plate and reduce the initial imperfections due to forming, t is the plate thickness and D is the diameter. The general formula for the welding cost of a shell element the cost of welding is as follows:

$$K_{F1} = k_F\left(\theta_W\sqrt{\kappa\rho V_1}\right) + k_F[1.3 \cdot 0.224 \cdot 10^{-3} t^2 (\kappa \cdot 3000)] \tag{9}$$

where θ_W is a difficulty factor expressing the complexity of the assembly and is set to 2, as used in [11]. Here, the first member calculates the time of the assembly, κ is the number of structural parts to be assembled, the second member estimates the time of welding. The formulas in Equations (9) and (10), and are obtained depending on the welding technology and weld type specified.

The welding cost for a complete unstiffened shell segment is found by combining the five elements using four circumferential butt welds. This implies that the welding costs [8] can be calculated for a shell segment:

$$K_{F2} = k_F\left(\theta_W\sqrt{5 \cdot 5\rho V_1}\right) + \ 1.3 \cdot 0.2245 \cdot 10^{-3} t^2 \cdot 4 \cdot D\pi \tag{10}$$

The cutting cost of n flat plate rings using acetylene gas is as follows:

$$K_{F3} = k_F \theta_C C_C t_r^{0.25} L_C \tag{11}$$

where θ_c is the difficulty factor for cutting and is taken as 3; and C_c is the cutting parameter with value $C_c = 1.1388 \times 10^{-3}$. The approximate value of the cutting length L_c is calculated as below:

$$L_C \approx D\pi n + (D - 2h_r)\pi n \tag{12}$$

The welding cost of n rings into the shell segment with double-sided GMAW-C fillet welds [8] is:

$$K_{F4} = k_F\left(\theta_W\sqrt{(n+1)\rho V_2}\right) + \ 1.3 \cdot 0.3394 \cdot 10^{-3} a_W^2 \cdot 2 \cdot D\pi n \tag{13}$$

The size of the weld for a ring of thickness t_r is $a_W = 0.5\ t_r$, but if the calculated value of aw is less than 3 mm, its value should be set to 3 mm in equation (13) ($a_W < 3$ mm $\rightarrow a_W = 3$ mm). The cost of painting can be calculated as:

$$K_P = k_p S_P \tag{14}$$

The surface area to be painted can be calculated as below:

$$S_P = 4R\pi 1500 + 5 \cdot 2 \cdot 2(D - h_r)h_r \tag{15}$$

where the paint cost factor is $k_P = 14.4 \times 10^{-6}$ \$/mm^2.

3.2. Constraints

3.2.1. Constraint 1

According to [10–14], the constraint on the height to thickness ratio of a flat ring stiffener is as follows:

$$g_1(x) = \frac{h_r}{t_r} - 0.375\sqrt{\frac{E}{f_y}} \leq 0 \tag{16}$$

where t_r is the ring stiffener thickness. The elastic modulus $E = 2.1 \times 10^5$ MPa and the yield stress $f_y = 355$ MPa for steel.

3.2.2. Constraint 2

To prevent local shell buckling, the sum of the axial (a) and bending (b) stresses should be less than the critical buckling stress value [8,16]:

$$g_2(x) = \sigma_a + \sigma_b - \sigma_{cr} = \frac{G_W}{D\pi t} + \frac{M}{\pi(D/2)^2 t} - \frac{f_y}{\sqrt{1+\gamma^4}} \leq 0 \tag{17}$$

where:

$$\gamma^2 = \frac{f_y}{\sigma_a + \sigma_b}\left(\frac{\sigma_a}{\sigma_{Ea}} + \frac{\sigma_b}{\sigma_{Eb}}\right) \tag{18}$$

$$\sigma_{Ea} = (1.5 - 50\beta)\, C_a \, \frac{\pi^2 E}{12(1-v^2)} \left(\frac{t}{L_r}\right)^2 \tag{19}$$

$$\sigma_{Eb} = (1.5 - 50\beta)\, C_b \, \frac{\pi^2 E}{12(1-v^2)} \left(\frac{t}{L_r}\right)^2 \tag{20}$$

$$C_a = \sqrt{1 + (\rho_a \xi)^2} \tag{21}$$

$$C_b = \sqrt{1 + (\rho_b \xi)^2} \tag{22}$$

$$\rho_a = 0.5 \left(1 + \frac{D/2}{150t}\right)^2 \tag{23}$$

$$\rho_b = 0.5 \left(1 + \frac{D/2}{300t}\right)^2 \tag{24}$$

$$\xi = 0.702 \cdot Z \tag{25}$$

$$Z = \frac{2L_r^2}{Dt} \sqrt{1 - v^2} \tag{26}$$

$$L_r = \frac{L}{n+1} \tag{27}$$

The shell buckling strength should be multiplied by the imperfection factor (1.5–50 β), where β is a reduction factor derived by Farkas [11]. Firstly, Farkas [11] derived a differential equation using the bending theory of cylindrical shells. Then, an approximate formula in Equation (28) for maximum radial deformation was obtained from the solution of this equation. Using the maximum radial deformation limits proposed by The European Convention for Constructional Steelwork (ECCS), the imperfection factor and reduction factors given above were obtained. The solution of this equation The detailed derivation of it is presented in [11]:

$$0.04\sqrt{0.5Dt} \le u_{max} \le 0.08\sqrt{0.5Dt} \tag{28}$$

Introducing a reduction factor of β for which:

$$0.01 \le \beta = \frac{u_{max}}{\sqrt{8Dt}} \le 0.02 \tag{29}$$

$$\beta < 0.01 \rightarrow \beta = 0.01$$

$$\beta > 0.02 \rightarrow \beta = 0.02 \tag{30}$$

The maximum radial deformation of a shell caused by the shrinkage of a circumferential weld is:

$$u_{max} = 0.64\, A_{Tt} \sqrt{\frac{D/2}{t}} \tag{31}$$

where A_{Tt} is the area of specific strains near the weld and is calculated for steel as follows [8]:

$$A_{Tt} = 0.844\; 10^{-3} Q_T \tag{32}$$

For the calculation of residual deflection the Okerblom-method is used, which has been adopted by Farkas and Jármai [10], Farkas [11]. The specific heat induced by welding can be calculated for butt welds as follows:

$$Q_T = 60.7A_w \tag{33}$$

$$t \leq 10\,mm \rightarrow A_w = 10t \tag{34}$$

$$t > 10\,mm \rightarrow A_w = 3.5t \tag{35}$$

where A_w is the cross-sectional area of the weld and its commonly used values are given in Equations (34) and (35) when estimating the cost of making a butt weld.

3.2.3. Constraint 3

The panel ring buckling constraint for a ring stiffener [8,16] is calculated as follows:

$$g_3(x) = h_r t_r - \left(\frac{2}{Z^2} + 0.06\right) L_r t \geq 0 \tag{36}$$

$$I_r = \frac{h_r^3 t_r}{12} \cdot \frac{1+4\omega}{1+\omega} \geq \left(\frac{\sigma_{max} t (D/2)^4}{500 E L_r}\right) \tag{37}$$

$$R_0 = R - y_G u_{max} = 0.64\, A_{Tt} \sqrt{\frac{D/2}{t}} \tag{38}$$

$$y_G = \frac{h_r}{2(1+\omega)} \tag{39}$$

$$\omega = \frac{L_e t}{h_r t_r} \tag{40}$$

$$L_e = min\,(L_r, L_{e0} = 1.5\sqrt{0.5Dt}) \tag{41}$$

3.2.4. Constraint 4

The natural frequency should be less than the rotation frequency of the blades:

$$g_{4(x)} = 1.75 \sqrt{\frac{EI_x}{L_{total}^3 (G_W + 0.23\, W_{tower})}} - 1.1\, f_{blade} \leq 0 \tag{42}$$

where L_{total} is the total height of the tower; G_W is the total mass of the rotor and nacelle at the top of the wind turbine; W_{tower} is the weight of the tower; and I_x is the moment of inertia. W_{tower} and I_x are obtained by:

$$I_x = \pi (0.5D)^3 t \tag{43}$$

$$W_{tower} = \pi D t L_{Total}\, \rho \tag{44}$$

4. Estimation of Wind Loads on Wind Turbine Tower

Wind load on a structure depends on several factors such as wind velocity, surrounding terrain and the size, shape and dynamic response of the structure. Conventional theory assumes that the horizontal wind load pressures act normally on the face of the structure. Computations for wind in all directions are performed to find the most critical loading condition. In this study, the most common procedure introduced in the Eurocode Part 2–4 [27] is used to calculate wind loads on wind turbine tower.

According to the Eurocode Part 2–4 [27], the average wind force F_W acting on a structure or a structural component (see Figure 3) can be determined by using:

$$F_w = c_e(z) q_{ref} c_s c_d c_f A_{ref} \tag{45}$$

where z is the reference height for external wind action; A_{ref} is the reference area of the structure or structural element; c_s and c_d is the size factor and the dynamic factor, respectively. The structural factor $c_s c_d$ should take into account the effect of wind actions from the nonsimultaneous occurrence of peak wind pressures on the surface (c_s) together with the effect of the vibrations of the structure due to turbulence (c_d). c_f is the force factor for the structure or structural element. q_{ref} is the reference velocity pressure in N/m^2 and $c_e(z)$ is the exposure factor at height z.

The reference velocity pressure (q_{ref}) is calculated from the basic value of the reference wind speed (v_{ref}) at different heights with an air density of ρ =1.25 kg/m^3 as follows:

$$q_{ref} = \frac{\rho}{2} v^2{}_{ref} \tag{46}$$

The exposure factor at height z can be found as:

$$c_e(z) = c^2{}_r c^2{}_t (1 + 7 l_v) \tag{47}$$

where l_v is the turbulence intensity and can be defined by:

$$l_v = \frac{k_r}{c_r c_t} \tag{48}$$

$$c_r = k_T \ln\left(\frac{z}{z_0}\right) \tag{49}$$

where k_r is the turbulence factor; The recommended value for k_r is 1,0 in [8]; k_T is the terrain factor and c_t is the orography factor; z_0 is the roughness length and is determined between 0.003 and 1 depends on the ground roughness and the distance with uniform terrain roughness in an angular sector around the wind direction. The values of k_T, c_t and z_0 can be obtained for sea or level area from tables and graphs in [13]. The force factor is given by [13]:

$$c_f = \psi_\lambda c_{f0} \tag{50}$$

where ψ_λ is the end-effect factor and c_{f0} is the force coefficient of structures or structural elements without free-end flow. c_{f0} is presented as a function of the Reynolds number (R_e) in [8]

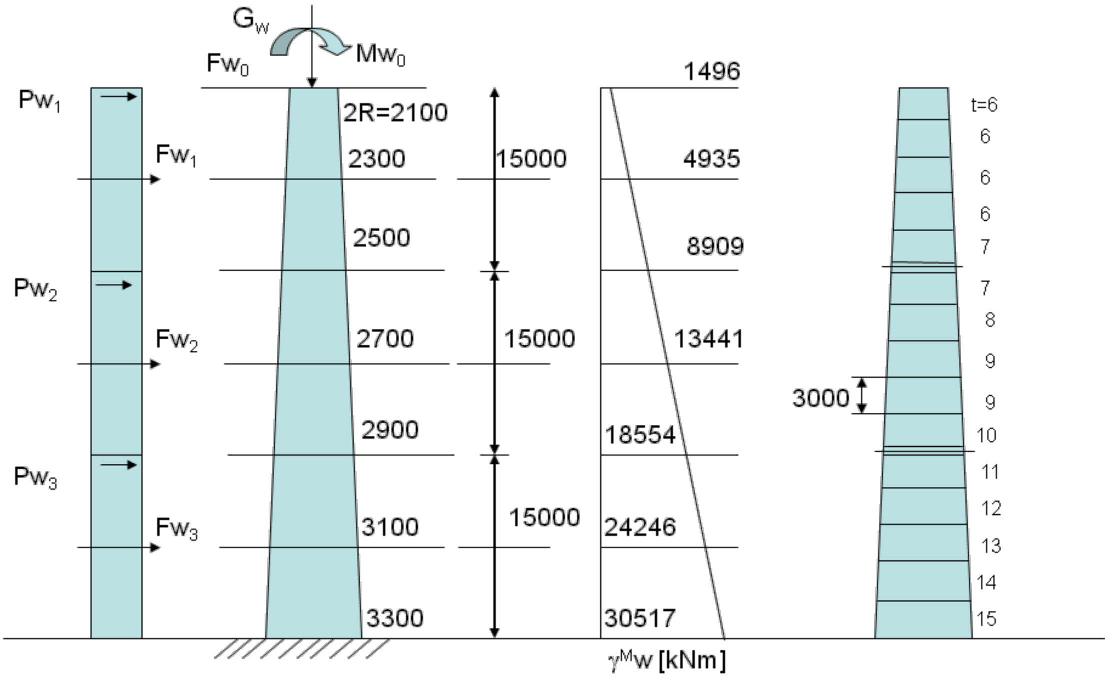
The uniformly distributed wind loads for the three shell segments indicated by P_{w1}, P_{w2} and P_{w3} in Figure 2 are calculated by the relation:

$$P_w = q_{ref} c_s c_d c_f D \tag{51}$$

where D is the average diameter of the wind turbine tower.

In this paper, optimization is performed for the three shell segments using an average diameter and bending moment. Assuming that the tower behaves like a cantilever beam with a concentrated loads acting in the middle of every shell segment, the bending moments are found as seen in Figure 3.

Figure 3. The 45 m wind turbine tower model used in [8].



5. Developed Virtual Tool for Particle Swarm Optimization

Physics-based modeling and simulation is important in all engineering problems. The development of computer software and hardware makes it possible to numerically solve complex mechanical and structural problems such as wind turbine design. In-house codes are primarily used for research projects and graduate studies; commercial packages are widely used to solve almost every engineering problem. In this study, a computer program is developed using MATLAB's m-files for the particle swarm optimization of wind turbine towers. MATLAB is a high-performance language for technical computing. The developed program has graphical user interfaces (GUIs) and easy-to-use design steps for a novice to design a wind turbine tower and find optimization results depending on design variables such as the wall thickness, outer diameter of the tower, tower height and tower weight. The flowchart of the developed computer program is given in Figure 4. The main interface is basically composed of three main areas: the PSO parameters, the problem specification and the obtained results. The required input values can be inserted in GUI's window, as shown in Figure 5. The right side of the window is reserved for user-specified parameters required for executing the particle swarm algorithm. The movements of the particles are shown on the left side of the window. Hence, designer can see the calculated values of parameters during the process of particle swarm optimization on the graph. The main idea of this program is to make it easier for the designer to try new parameters easily and quickly during the design process of the wind turbine tower. Furthermore, similar virtual tools have the potential to impact teaching and learning in a classroom.

Figure 4. The flowchart of the developed computer program.

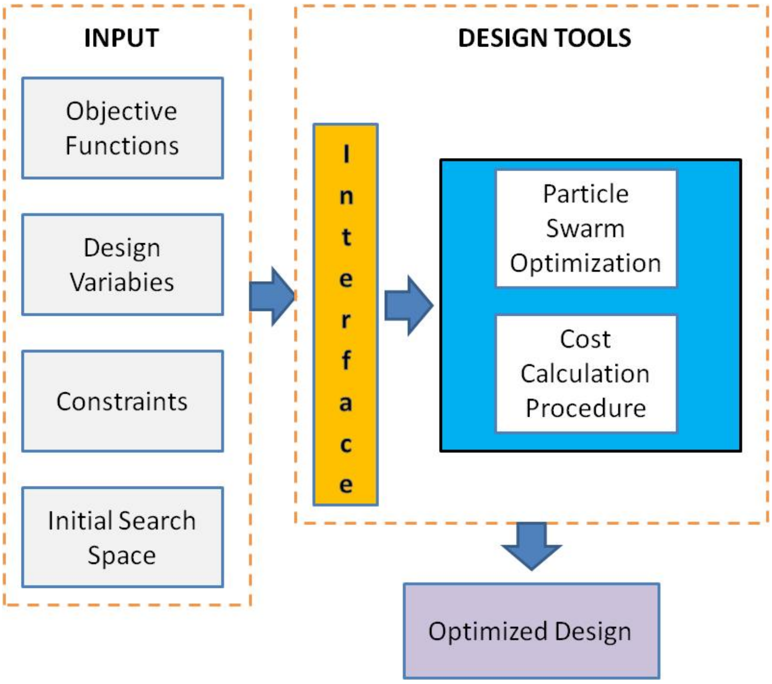
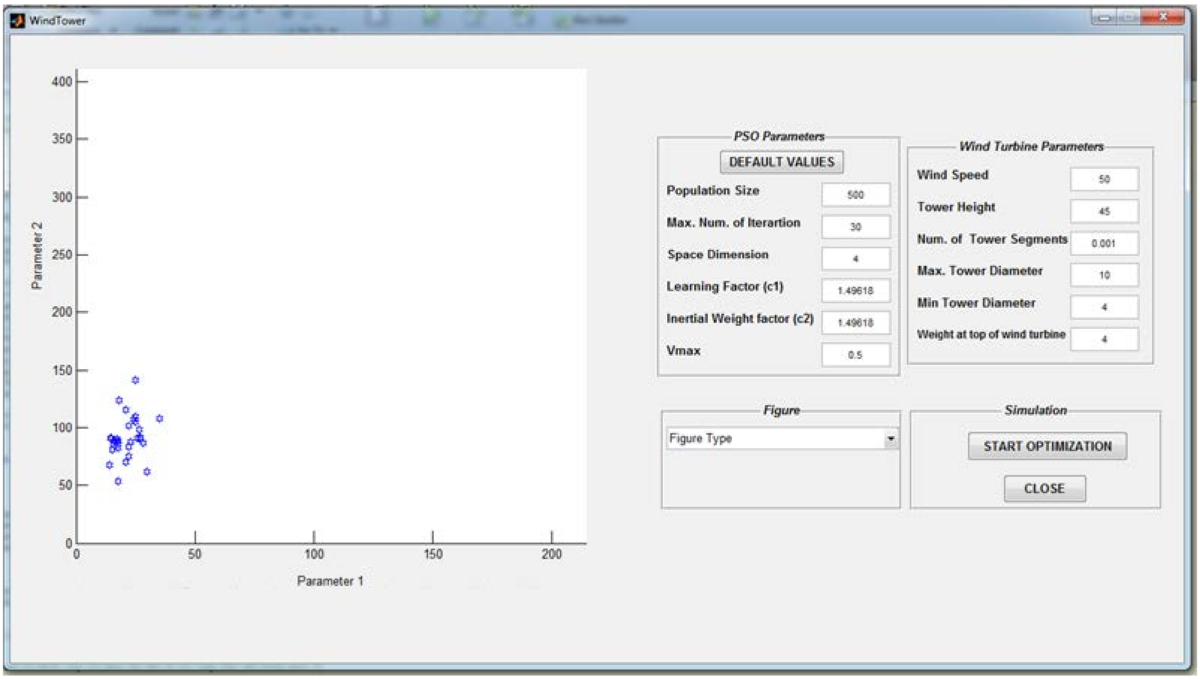


Figure 5. A view of the developed computer program.



6. Results and Discussions

In this paper, a computer program, WindTower, is validated using a numerical optimization problem for the structural design of the wind turbine tower proposed by Lavassas *et al.* and Uys *et al.* [6,8]. Numerical data for a sample wind turbine tower is given in Table 1 and Figure 2. In this study, particle swarm optimization parameters are selected to obtain the best solution after a number of trials and searching the literature. In this example, for PSO, the value of each learning factor (c_1,c_2) is taken as 1.49618. Empirical results have shown that the learning factors with $c_1 = c_2 = 1.49618$ provide good convergent behavior [17,23]. The maximum velocity (v_{max}) and the inertia weight factor (w) are selected as 0.5 and 0.9, respectively. The maximum generation number is 500 and the population is 50 for this example. The minimum and maximum values of the design variables are determined according to standard practice rules and are given in Table 2. The wind load acting on the shell tower is calculated according to Eurocode 1 Part 2–4 [27] (Table 1). The wind force and bending moment acting on the top of a 45 m tower for a 1MW wind turbine in Greece are given by Lavassas *et al.* and Uys *et al.* [6,8]. The load due to the self-weight of the nacelle is also considered.

Table 1. An example of numerical data.

Input Data			
P_{w1}	6.334 kN/m	F_{W0}	282 kN
P_{w2}	6.883 kN/m	Safety factor	1.5 -
P_{w3}	6.864 kN/m	Yield stress	355 MPa
G_W	950 kN	Wind speed [1]	36 m/s
M_{W0}	997 kNm	Blade frequency [1]	0.37 Hz

[1] This value is taken from [6] and [8].

Table 2. Minimum and maximum values of the design variables.

Design variables	Minimum	Maximum
t	4 mm	40 mm
h_r	20 mm	200 mm
t_r	4 mm	20 mm
D	1750 mm	3500 mm

The mass and costs for five ring stiffeners are calculated in Table 3. These results agree well with [8], and the results obtained using the particle swarm optimization algorithm with fly-back mechanism are better than those obtained by the Rosenbrock search algorithm in [8]. The total cost and mass are reduced by 5.2% and 4.4%, respectively. Furthermore, the total tower mass is approximately 30% lower when compared with the wind turbine tower proposed in [6]. Table 4 represents the optimum values of design parameter for best solution. All optimization results presented in this paper are the best values of 15 runs. Since the optimization results in Table 3 are agreed with the results in [8] the trial number is set to 15. The developed computer program allows changing trial number.

Table 3. Comparison of the optimization results.

Shell parts	Reference [8]			This study		
	Mass	K-K_P	K	Mass	K-K_P	K
Top	5,398 kg	12,096 $	15,316 $	5,278	11,625 $	14,770 $
Middle	9,472 kg	19,772 $	23,574 $	9,456	19,761 $	23,453 $
Bottom	15,648 kg	30,941 $	35,330 $	14447	27,962 $	32,201 $
Total	30,518 kg	62,809 $	74,220 $	29,181	59,348 $	70,424 $

Table 4. Optimization results for design parameters.

Shell parts	Wall thickness	Stiffener thickness	Stiffener height
Top	6.30 mm	4.60 mm	41.50 mm
Middle	9.20 mm	5.30 mm	47.30 mm
Bottom	11.50 mm	6.50 mm	57.50 mm

The results of PSO for wind turbine tower shown in Figure 5 including the worst value, the best value and the mean value of total cost are presented in Table 5. These results are obtained after 15 runs. This study examines the effects of increasing the wall thickness, diameter at the base and taper ratio on the mass and cost of a tower using a wind turbine tower with a height of 45 m with an external base diameter of 3.30 m and a diameter of 2.10 m at the top. Each segment of the tower (top, middle and bottom) is analyzed for various wall thicknesses. The optimization results for the top, middle and bottom segments are presented in Tables 4–8. The results show that the diameter decreases as wall thickness increases. In addition, the mass and cost increase.

Table 5. Results of PSO for wind turbine tower.

Objective function K in 15 runs					
Shell parts	**Worst (Max) ($)**	**Best (Min) ($)**	**Mean ($)**	**Standard deviation ($)**	**Mean time (s)**
Top	15,381	14,770	14,928	2,259	99.07
Middle	23,597	23,453	23,482	4,501	104.79
Bottom	35,276	32,201	32,755	5,238	106.12
Total	74,254	70,424	71,165	11998	106.88

Table 6. Optimization results for the bottom segment.

Wall thickness	Average outer diameter	Mass	Stiffener height	Stiffener thickness	K
12 mm	3,153 mm	13,998 kg	57.6 mm	6.5 mm	30,822 $
13 mm	2,916 mm	14,023 kg	61.8 mm	7.2 mm	31,137 $
14 mm	2,754 mm	14,263 kg	44.6 mm	5.1 mm	31,372 $
15 mm	2,718 mm	15,088 kg	56.9 mm	6.7 mm	33,246 $
16 mm	2,720 mm	16,094 kg	61.7 mm	6.9 mm	35,210 $

Table 7. Optimization results for the middle segment.

Wall thickness	Average outer diameter	Mass	Stiffener height	Stiffener thickness	K
9 mm	2,904 mm	9,670 kg	47.3 mm	5.3 mm	22,853 $
10 mm	2,575 mm	9,529 kg	48.4 mm	5.6 mm	22,715 $
11 mm	2,360 mm	9,606 kg	37.9 mm	4.5 mm	22,834 $
12 mm	2,225 mm	9,882 kg	39.4 mm	5.0 mm	23,564 $
14 mm	2,208 mm	11,434 kg	57.9 mm	5.4 mm	26,878 $

Table 8. Optimization results for the top segment.

Wall thickness	Average outer diameter	Mass	Stiffener height	Stiffener thickness	K
7 mm	2,027 mm	5,248 kg	41.4 mm	4.6 mm	14,408 $
8 mm	1,805 mm	5,341 kg	74.5 mm	8.7 mm	15,189 $
9 mm	1,807 mm	6,016 kg	49.0 mm	5.4 mm	16,210 $
10 mm	1,772 mm	6,558 kg	42.1 mm	5.3 mm	17,364 $
12 mm	1,779 mm	7,896 kg	46.1 mm	5.6 mm	20,241 $

A parametric study is carried out for towers with three different tapered ratios. The taper ratio is the ratio of the difference between the top diameter and the base diameter to the tower height. To obtain different taper ratios, the diameter at the top is fixed at 2100 mm, and the base diameter is increased. Table 9 compares the results for towers with three different base diameters. As the base diameter increases, the wall thickness decreases from 14 mm to 11 mm at the bottom segment. In this study, varying the taper ratio has a small effect on the mass and cost.

Table 9. Optimization results depending on the taper ratio.

Taper ratio	Mass	K	Wall thickness range
0.018	28,876 kg	69,452 $	6.5–14.0 mm
0.020	28,900 kg	69,417 $	6.5–13.5 mm
0.027	28,880 kg	70,404 $	6.5–12 mm
0.031	28,760 kg	69,670 $	6.5–11.5 mm
0.038	29,417 kg	70,812 $	6.0–11.0 mm

For a fixed taper ratio, the impact of increasing the diameter on the mass and cost is investigated. Table 10 shows the variation of the cost, mass and wall thickness as the diameter increases. The table shows that the minimum mass and minimum cost can be obtained by varying the diameter. According to the optimization results, as the diameter decreases, the wall thickness increases. This case affects both the mass of the material and the welding, manufacturing and painting costs significantly. It is not possible to clearly describe the influence of the variation of the design variables. Therefore, to find the optimum results, each case is examined and analyzed under specific conditions. These results are in agreement with the optimization results of a conical shell cantilever column obtained by Farkas *et al.* [15]. Because the labor and material cost factors can change in different countries, the optimization results may vary.

Table 10. Optimization results depending on the same taper ratio.

	Diameter base	Diameter top	D/t	Mass	K
Top	1,600 mm	2,800 mm	234	5,145 kg	14,272 $
Middle	1,600 mm	2,800 mm	183	9,733 kg	23,706 $
Bottom	1,600 mm	2,800 mm	173	14,416 kg	32,207 $
Total	1,600 mm	2,800 mm	-	29,294 kg	70,185 $
Top	1,800 mm	3,000 mm	290	5,080 kg	14,109 $
Middle	1,800 mm	3,000 mm	224	9,510 kg	23,155 $
Bottom	1,800 mm	3,000 mm	205	14,075 kg	31,862 $
Total	1,800 mm	3,000 mm	-	28,665 kg	69,126 $
Top	2,100 mm	3,300 mm	371	5,278 kg	14,770 $
Middle	2,100 mm	3,300 mm	281	9,456 kg	23,453 $
Bottom	2,100 mm	3,300 mm	254	14,447 kg	32,201 $
Total	2,100 mm	3,300 mm	-	29,181 kg	70,424 $
Top	2,300 mm	3,500 mm	416	5,540 kg	15,138 $
Middle	2,300 mm	3,500 mm	322	9,699 kg	23,481 $
Bottom	2,300 mm	3,500 mm	277	13,909 kg	31,396 $
Total	2,300 mm	3,500 mm	-	29,148 kg	69,929 $
Top	2,500 mm	3,700 mm	473	5,687 kg	15,884 $
Middle	2,500 mm	3,700 mm	360	9,846 kg	23,545 $
Bottom	2,500 mm	3,700 mm	321	14,056 kg	31,246 $
Total	2,500 mm	3,700 mm	-	29,589 kg	70,675 $

7. Conclusions

In this study, a virtual tool was developed to optimize the cost of a wind turbine steel tower with ring stiffeners using a particle swarm algorithm. A wind turbine tower model existing in the literature was used to verify the optimization results obtained. In the present study, an optimization problem for wind turbine steel towers with ring stiffening was considered using particle swarm optimization algorithm. The effects of design variables such as the wall thickness, dimension of the ring stiffener and tower diameter are investigated, and the optimum value was found for each case. It is found that the variations of the wall thickness and diameter have an important effect on the mass and cost of wind turbine towers. The optimization results were verified with previous optimization results using different optimization algorithms. When obtained results are compared with [8] the total cost and mass were reduced by 5.2% and 4.4%, respectively. Furthermore, the total tower mass was approximately 30% less than the wind turbine tower proposed in [6]. It should be noted that these results and the developed program can be used for reference for similar structural design problems.

Though the particle swarm optimization is one of the new methods for the analysis of many structural problems, it seems to be very promising in the structural design problems. Algorithmic optimization is becoming popular for structural design, but it is still not widely used in industry. Further development is needed to make computing approaches more accurate and consistent, and along with improved optimization tools allow designers to make more reliable and efficient structural designs. One of the inhibitors to the use of optimization algorithms in industry is optimization tools with interactive GUI. Future success of structural optimization is in application of expert knowledge with existing and emergent algorithmic and computing approaches to large-scale designs such as wind turbine tower. Therefore, the virtual tool introduced in this study may lead to new studies and applications for a cost-effective wind turbine tower design. This virtual tool and optimization results will be developed to help designing efficient structures and solve actual design problems.

Acknowledgments

A part of this research was supported by Uludag University, Scientific Research Center under grant BAP-YDP(M) 2012/10 and Texas Tech University, Mechanical Engineering Department DE-FG36-06GO86092.

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