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Incorporation of Life Cycle Models in determining Optimal Wind Energy Infrastructural Provision

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ABSTRACT: The deployment of wind energy has grown rapidly over the last two decades with an average annual growth rate of more than 26% since 1990. During this period the development and innovation of wind turbines has resulted in continual growth in wind turbine size with output ranges of 10-15MW likely to be deployed by 2020. This increased output has a knock-on effect on the growth of rotor diameters and tower heights. Wind turbine towers are required to become taller, stronger and stiffer in order to carry the increased weight and associated structural loading. Consequently, the dimensions of the tower cross-sections must be increased which results in manufacturing and transportation difficulties as well as increased material costs. Thus, this paper focuses on the development of wind energy technology over the last two decades and the optimisation techniques cited in current literature. From this, a multi-objective optimisation problem is defined as maximising the structural performance of wind turbine towers while simultaneously reducing the life cycle costs and emissions associated with electricity generation from wind. A multi-objective optimisation model based on a harmony search algorithm is presented. This model is proposed to be developed further in order to determine a set of optimal combinations known as Pareto optimal solutions, which will allow a trade-off between the life cycle costs and emissions. Findings from the continuing research are envisaged to support the deployment of large scale wind turbines both onshore and offshore from structurally more promising, economically more competitive and environmentally greener towers.

KEY WORDS: Optimisation; Life cycle cost; Life cycle assessment; Wind turbine towers; Steel; Concrete; Wind turbines.

1 INTRODUCTION

Wind energy has gained popularity worldwide as countries strive to increase the production of renewable energy technologies in order to mitigate global warming and meet future energy demand. Over the last decade the utilisation of wind energy worldwide has grown rapidly with an average annual growth rate of about 30% [1].

This is driven by the implementation of legislation such as the European Commission's Renewables Directive 2009/28/EC and Strategic Energy Technology Plan (SET-Plan) which support the development of cost effective low carbon energy technologies such as wind energy [2–4]. This framework is required to help meet the 2020 targets to reduce greenhouse gas (GHG) emissions by 20% and ensure that 20% of Europe's energy comes from renewable energy sources [3].

To achieve these targets the European Wind Initiative's main objective is to maintain technology leadership in both onshore and offshore wind energy by making onshore and offshore wind the most competitive energy sources by 2020 and 2030 respectively [4]. This has led to research activities into the development of the technology used in wind turbines and their manufacture both for onshore and offshore applications with the aim of reducing the cost of wind energy. As a result, a large prototype offshore wind turbine with 10-20MW output range will be developed and demonstrated [4].

Furthermore, the development and innovation of wind turbines over the last two decades has resulted in continual growth in size with output ranges of 10-15MW likely to be deployed by 2020. This increased output has a knock-on effect on the growth of tower heights and rotor diameters requiring wind turbine towers to become taller, stronger and stiffer to carry the increased weight and associated structural loading.

The predominant designs for worldwide wind turbine towers are tubular steel tower solutions primarily due to the mastering of their design and ease of installation [5]. However, with increasing steel prices, manufacturing, transportation and vibrational issues, concrete towers are becoming a viable, if not optimal solution for taller towers [5–8].

Furthermore, research into reducing the cost and improving the design of these towers has been limited and with the ever increasing size of the next generation wind turbines the need to optimise the wind turbine tower structure is vital to reduce the cost of wind energy [9].

This paper focuses on the development of wind energy technology over the last two decades and the optimisation techniques cited in past publications. From this, the proposed optimisation methodology for the continuing research into the optimisation of wind energy infrastructures is defined and discussed.

2 BACKGROUND AND SIGNIFICANCE

2.1 *Industrial background*

There is a large amount of research papers and reports highlighting wind energy as the world's fastest growing energy source [1], [2], [4], [9–12]. The annual European installed wind energy capacity has increased steadily over the last 17 years from 814MW in 1995 to 9,616MW in 2011 with an average annual growth rate of 15.6% [13]. During this period the trend was to have large scale and more powerful wind turbines in order to capture more energy and to bring down the cost of wind energy generation. This resulted in the sizes of the turbines, including blade length, tower height and generation capacity becoming larger and larger [1].

Moreover, rotor diameters have increased eight fold and the average capacity of wind turbines installed around the world during 2007 was 1.5MW whereas now Enercon operates the world's largest onshore wind turbine rated at 7.5MW at a hub height of 135m [6]. Currently, Clipper is planning to manufacture a 7.5MW turbine with both Clipper and Sway developing 10MW prototypes for offshore deployment [1].

Due to the tendency towards larger wind turbines on taller towers a number of difficulties has arisen in relation to the predominately used tubular steel tower designs. As a result, manufacturing and transportation difficulties arise as the dimensions of the tower cross sections must be increased to accommodate the increased weight [5], [6], [8].

For example the lower sections of steel towers 90m or greater can no longer be transported by road due to the European road width and bridge clearance limits [6]. Additionally, shaping of the steel sheets for the steel towers require special machines for diameters greater than 4.5m which are not always available in steel fabrication workshops [5]. In Ireland, for example, no indigenous steel industry exists; therefore steel towers are designed, fabricated and imported from abroad; which adds to transport costs and transport related GHG emissions.

Moreover, it has been established that as towers go beyond 85m problems arise with the current tubular steel tower designs due to the vibrations induced by the wind turbine [14]. This has led to alternative proposals such as the use of precast or in-situ prestressed and reinforced concrete and/or hybrid materials [8], [14], [15]. Also extensive research is being carried into the development of glass fiber reinforced polymers for tower solutions [16].

According to Tricklebank et al. [8] the use of concrete in the wind energy sector has been 'predominantly in foundation applications either to form gravity foundations or pile caps'. Nevertheless concrete tower solutions are being used onshore by at least three wind turbine manufacturers Enercon, GE Wind and Nordex. Yet no manufacturers have exploited their use offshore.

Recently Enercon completed the Castledockrell windfarm in the southeast of Ireland which consists of eighteen 2.3MW turbines on 84m precast concrete towers; this was the first time this type of tower had been used in Ireland [17]. More recently Enercon installed Europe's highest elevation wind turbine on a 83m precast concrete tower in the Swiss canton of Valais 2,465m above sea level [18]. This tower solution was chosen due to the extreme conditions and the technological and logistical challenges at this location.

Nordex have solved the logistical and resonance frequency problem of towers with a hub height of over 100m by developing a special concrete/steel hybrid tower [8], [19]. Up until 2006, they only used steel towers but have recognised that concrete offers a relatively inexpensive alternative. The tower solution involves the use of locally supplied materials and ensures an optimal tower height to make the most of the prevailing conditions [19].

This underlines concrete's adaptability in terms of manufacture and transport compared to steel as well as the ability to alter the tower design for particular scenarios. This influences the challenge to optimise tower designs which are subject to aggressive environments and vibrational behaviour. Additionally, these structures must be cost effective and possess minimal construction and maintenance GHG emissions over their design life.

Although some research has been conducted into the optimisation of wind turbine towers limited research has focused on their structural performance, cost and environmental impact [15], [20–22]. Consequently, this gives rise to the need to identify an optimal tower solution based upon the trend of increasing wind turbine sizes and hub heights in order to reduce the cost of wind energy.

2.2 Research significance and objective

The wind turbine tower structure is the most material consuming part of the wind turbine system (rotor, nacelle and tower) accounting for 26% of the material cost of the system [9]. However, the drive to improve its design or reduce its material consumption and cost has been limited. Thus, this presents an opportunity to investigate the application of new materials for the tower structure.

This requires a thorough investigation into the material selection process for the tower where the material will need to withstand the wind turbines structural demands while minimising cost and environmental impact.

Hence, the purpose of this research is to identify an optimal solution for the tower design with the objective of maximising the structural performance while simultaneously reducing the cost of wind energy and its associated environmental impact.

3 AN OVERVIEW OF OPTIMISATION

In mathematics, optimisation refers to the process of choosing the best alternative from some set of available alternatives [23]. This means solving problems in which one seeks one or more feasible solutions to minimise or maximise one or more objective functions by systematically choosing the solutions from within an allowed set [23].

Typically, optimisation is used to minimise cost and/or maximise performance levels subject to engineering or regulatory constraints. Over the past few decades, designers have spent considerable effort to integrate design techniques from different disciplines. This integration is motivated by the idea that better designs can be achieved through concurrent engineering and the commercial imperatives of reducing both design time and cost [7], [23].

According to Baños et al. [24] 'computational optimisation can be defined as the process of designing, implementing and testing algorithms for solving a large variety of optimisation problems'. This method of optimisation includes the disciplines of mathematics to formulate the model, computer science for algorithmic design and analysis, and software engineering to implement the model [24].

Although computational optimisation methods have focused on solving single objective problems there exists multi-objective algorithms for the simultaneous optimisation of several objectives [24]. As a result, large numbers of optimisation techniques for handling multi-objective

optimisation problems are cited in over 5,600 publications up to January 2011 [25].
The purpose of a multi-objective optimisation problem (MOP) is to find a vector of the design space that optimises a set of objectives and meets a set of constraints. The objective functions are the quantities that the designer wishes to maximise, minimise or match a certain value. The mathematical problem in standard form for minimisation is formulated as follows [26]:

$$\text{Minimise: } \mathbf{f(x)} = \{f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_M(\mathbf{x})\} \quad (1)$$

$$\text{subject to: } g_i(\mathbf{x}) \leq 0, \quad i = 1,\ldots,L \quad (2)$$

$$h_j(\mathbf{x}) = 0, \quad j = 1,\ldots,K \quad (3)$$

$$x_l^l \leq x_l \leq x_l^u \quad l = 1,\ldots,N \quad (4)$$

where:
$\mathbf{x} = (x_1,\ldots,x_N)$ is the design vector with N variables;
f (x) is the objective vector with M objective functions; and
g and h are the inequality and equality constraints respectively on the design vector and the constraints (4) are called boundary constraints.
When $M = 1$, there is only one objective function to be minimised and the problem is referred to as single objective optimisation. In this case, classic optimisation methods or evolutionary methods such as genetic algorithm (GA) or simulated annealing (SA) can be used to solve the problem [26]. When $M > 1$, the problem is known as multi-objective optimisation. In this case, minimising several objectives at the same time may not be possible and the concept of a Pareto solution must be used [26].
According to Maginot [26] the general consensus of engineers and mathematicians working in the area of optimisation is that the Pareto optimal set may contain information that can help the designer to make a decision and thus arrive at better trade off solutions. When solving a MOP with conflicting objectives a unique solution generally does not exist; but a set of non-dominated solutions known as the Pareto solution exists. A feasible design point is said to be Pareto optimal if no other feasible design can improve some of the objectives without simultaneously being detrimental to others [26].
In order for the decision maker to quickly assess the trade-off between the two objectives a Pareto front needs to be plotted. [27]. The plot of the objective functions whose non-dominated vectors are in the Pareto optimal set is called the Pareto front. Figure 1 shows an example of a Pareto front for a MOP whose objectives are $CO_{2\text{-eq}}$ emissions and life cycle cost. These objectives are naturally conflicting where the cost of environmental friendly materials is usually higher than conventional materials. As a result, the need for a multi objective optimisation approach is required.

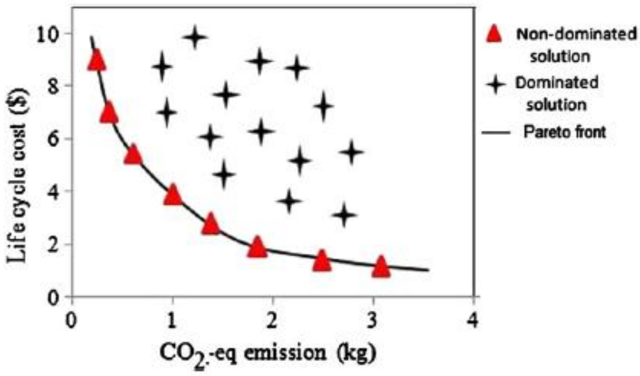

Figure 1. A sample Pareto front [27]

In literature, several algorithms have been suggested for the approximation of Pareto fronts [7], [24–26]. Among them are evolutionary multi-objective optimisation algorithms (EMOA) which have become increasingly popular and have attracted a considerable amount of research effort over the last 20 years [25]. They are considered to be robust with design flexibility as they can be applied for different representations and adapted to different computing environments [26].
A survey cited by Zhou et al. [25] indicates the research work on EMOA from different aspects. Some are based mainly on generic methodologies, theoretical developments and special methods for MOPs, for example SA, particle swarm optimization (HPSO) and harmony search (HS).
Traditional mathematical techniques such as linear programming (LP), non-linear programming (NLP) and dynamic programming (DP) have frequently been used for solving optimisation problems [28]. These techniques can guarantee global optima in simple and ideal models but for real world problems there are some weaknesses. In LP, considerable losses occur when a linear ideal model from a non-linear real world problem is developed, in NLP, if the functions used in computation are not differentiable, the solving algorithm may not find the optimum and in DP, an increase in the number of variables would exponentially increase the number of evaluations of the recursive functions and tax the core-memory [28].
In order to eliminate the above weakness of mathematical techniques, heuristic optimisation techniques based on simulation have been introduced. These allow a good solution to be found within reasonable computation time and with reasonable use of memory. These techniques include GA which uses reproduction, crossover and mutation operators to define fitness and to create new solutions. The main characteristic of GA which differs from SA is the simultaneous evaluation of many solutions. This feature can be advantageous enabling a wide search and potentially avoiding convergence to a non-global optimum [28].
Harmony search (HS) is a new meta-heuristic technique and is inspired by the natural musical performance process that occurs when a musician searches for a better state of harmony [28]. In a HS algorithm, the solution vector is analogous to the harmony in music and the local and global search schemes are analogous to the musician’s improvisations. According to Pan et al. [29] the HS algorithm imposes fewer mathematical requirements and can be easily adapted for solving various kinds of engineering optimisation problems.

Numerical comparisons demonstrated that the evolution in the HS algorithm was faster than GA. The main difference between GA and HS is that HS makes a new vector from all the existing vectors (all harmonies in the harmony memory) while GA makes the new vector only from two of the existing vectors (the parents) [28]. Moreover, HS can independently consider each component variable in a vector while it generates a new vector whereas GA cannot because it has to keep the structure of a gene. As the GA is a global search algorithm which is based on the concepts from natural genetics [30].

Hence, the HS algorithm has captured much attention and has been applied to solve a wide range of practical optimisation problems, such as structural optimisation, cost reduction in power generation systems integrating large scale wind energy conversion systems, vehicle routing, combined heat and power economic dispatch, design of steel frames and transport energy modeling [29], [30].

From the optimisation methods considered and proposed in literature, a multi-objective optimisation approach with a HS algorithm currently presents itself as the most appropriate to the objective of the present work.

4 METHODOLOGY

4.1 Problem definition

The present problem involves maximising the structural performance of the wind turbine tower while simultaneously minimising the levelised cost of electricity production (LCOE) and the emissions intensity of electricity production (EIOE). Hence, the optimisation approach aims to minimise two objective functions, f_1 and f_2 represented by expressions (5) and (6) while satisfying the constraints of expression (7):

$$LCOE = f_1(x_1, x_2, .. x_n) \tag{4}$$

$$EIOE = f_2(x_1, x_2, .. x_n) \tag{5}$$

$$g_i(x_1, x_2, .. x_n) \leq 0 \tag{6}$$

The design variables $x_1, x_2, .. x_n$ and the parameters of the problem are all the data required to define a given wind farm whether onshore or offshore. The design variables are the magnitudes subject to optimisation, while the parameters are all the remaining data relating to the wind farm. The parameters of the tower are all the magnitudes taken as fixed data, including durability conditions, material density and design loads considered. The main design variables that will affect the LCOE and EIOE are the rotor diameter, wind turbine rating and hub height.

The constraints g_i are the tower limit states as well as the wind regime and wind turbine size. The tower limit state for each tower height will be defined as the minimum extreme displacement of the tower tip at the maximum mean hub height wind velocity [6].

4.2 Objective functions

The first objective LCOE is the ratio of the cost to produce the energy to the amount of energy that is produced and is given by:

$$\text{LCOE} = \text{NPC} \Big/ \sum_{i=1}^{n} \left(E_i (1+r)^{-i} \right) \tag{7}$$

where:
E_i is the electricity produced in year i (kWh);
r is the discount rate (%) ; and
n is the lifespan (years).
NPC is the life cycle net present cost of electricity generated given by:

$$\text{NPC} = \text{CC} + \sum_{\text{i=1}}^{\text{n}} \left[(\text{MC} + \text{OC})(1+r)^{-i} \right] + DC(1+r)^{-n} \tag{8}$$

where:
CC is the capital cost in year 0 (€);
MC is the maintenance cost in year i (€);
OC is the operating cost in year i (€);
DC is the decommissioning cost in year n (€); and
r is the discount rate (%).
The NPC covers the wind turbine costs including items such as transportation from factory to site, engineering services, grid connection, operation and maintenance (O&M) and decommissioning. Cost data for the various items associated with the wind energy facility are proposed to be obtained from industry sources and a meta-analysis of reported costs in publications.

The second objective seeks to minimise the EIOE due to the $CO_{2\text{-eq}}$ emissions that arise during the production and operation of the wind energy facility. The EIOE is given by:

$$\text{EIOE} = \text{LCE} \Big/ \sum_{i=1}^{n} (E_i) \tag{9}$$

where:
E_i is the electricity produced in year i (kWh); and
n is the lifespan (years).
LCE are the life cycle emissions of electricity generating given by:

$$\text{LCE} = \text{CE} + \sum_{\text{i=1}}^{\text{n}} \left[(\text{ME} + \text{OE}) \right] + DE \tag{10}$$

where:
CE are the capital related emissions in year 0 ($tCO_{2\text{-eq}}$);
ME are the maintenance emissions in year i ($tCO_{2\text{-eq}}$);
OE are the operational emissions in year i ($tCO_{2\text{-eq}}$); and
DE are the decommissioning emissions in year n ($tCO_{2\text{-eq}}$).
An emissions life cycle assessment (LCA) will be developed using a process based hybrid analysis which incorporates both process and input-output (I-O) analyses. By adopting the hybrid methodology the embodied $CO_{2\text{-eq}}$ for the wind farm can be obtained for each life cycle stage and in turn for the LCE.

4.3 Proposed optimisation methodology

A HS based optimisation process is proposed for searching for the wind turbine tower that has minimum LCOE and EIOE for a specific wind energy facility. This algorithm offers several advantages over traditional optimisation methods such as [31]; (a) it imposes fewer mathematical requirements and it does not require initial value setting of the decision variables, (b) it uses stochastic random searches, derivative information is unnecessary, (c) it generates a new vector after considering all of the existing vectors. The flow diagram of the optimisation model is illustrated in Figure 2.

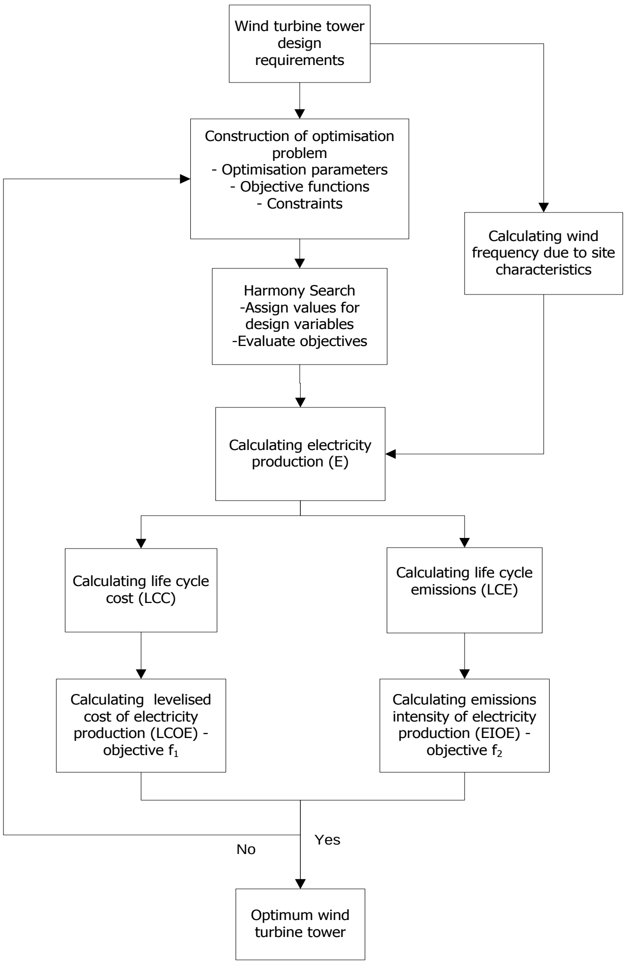

Figure 2. Flow diagram of the proposed optimisation model

The first step of the optimisation process is the determination of the fundamental design requirements and constraints such as the selection of the wind farm site, wind velocity, wind turbine rating and hub height. After the selection of the wind farm site, the wind frequency will be calculated using Weibull analysis.

After the design requirements are determined, the optimisation problem is constructed by selecting an appropriate objective function, optimisation parameters and constraints. The objective functions for this study are selected as LCOE and EIOE. The optimisation parameters are the wind turbine tower dimensions, namely height, wall thickness and diameter.

The optimisation process starts by assigning initial values of the design variables within the defined range of variables of the HS algorithm. Using the assigned design parameters, initially, the electricity produced (E) by each new design is calculated. Following the E calculation, the LCC and LCE are calculated for the wind turbine tower. Using E, LCC and LCE, the LCOE and EIOE are calculated using equations (8) and (10) respectively.

Next, based on the initial results, the HS algorithm sets new values for the design variables and another simulation is performed to evaluate the objectives of the new design. The new values of the design variables can be chosen either randomly or using the best obtained values which are already stored in the harmony memory (HM) of the algorithm. In case the new solution is better than the worst solution available in the HM, the worst solution is replaced by the new solution [27].

As the optimisation routine proceeds, step by step, the solutions stored in the HM become better and approach the optimum solution. The process is continued until a pre-specified maximum number of iterations are reached.

5 CONCLUSIONS

This paper set out to highlight the development of wind energy technology over the last two decades and its knock-on effect to wind turbine towers. An overview of the different optimisation techniques from past publications was conducted and from this a multi objective optimisation harmony search algorithm approach was deemed to be the most appropriate.

A description of the problem definition and objective functions was outlined where the optimisation process aims to find an optimal tower design that minimises life cycle costs and emissions. It remains for continuing research to study the effects of several wind turbine tower designs and to develop the optimisation model further using different optimisation techniques.

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