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Renewable Energy 136 (2019) 1190–1201

Contents lists available at ScienceDirect

Renewable Energy

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A new mathematical programming approach to wind farm layout problem under multiple wake effects

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ARTICLE INFO

Article history:
Received 23 December 2017
Received in revised form
27 August 2018
Accepted 24 September 2018
Available online 26 September 2018

Keywords:
Wind farm
Layout optimization
Wake effect
Non-linear programming

ABSTRACT

Wind farm layout optimization is one of the challenging problems in the field of renewable energy. In the present study, a new nonlinear mathematical model for layout of wind turbines under multiple wake effects is proposed considering two objective functions separately: maximization of total power production and minimization of cost per power. To incorporate multiple wake effects into the proposed model, Jensen's wake decay model is employed. It was proven that the proposed model has totally unimodularity property and according to this property, relaxation of binary decision variables related with the wind turbine locations makes the model relatively simple to solve. Computational study reveals that results of total power production and cost of power obtained from the proposed model outperform that of the previous studies in the literature on a set of example cases and therefore, can be used to layout more productive wind farms.

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1. Introduction

The use of renewable energy sources around the world has become obligate with the increasing energy demand. Because of the continuity and sustainability opportunities of renewable energy, it has been considered as an alternative energy resource in the developed countries. Wind energy becomes a key source of renewable energy because of its high potential to provide the required energy capacity. As World Wind Energy Association declared, the worldwide wind capacity has nearly doubled from the year 2012–2017 [1]. Approximately 5% of the world's electricity demand had been met by the wind turbines installed worldwide by the end of 2016 [17].

Investments in large wind farms consisting of many wind turbines have been increasing accompanying with the increasing demand on wind energy. Produced power by a wind farm is directly related to the number of turbines placed. On the other hand, locations of turbines have a considerable impact on total power production due to the wake effect, which is known as a modified wind flow in terms of both decreased wind speed and increased turbulence intensity received by a turbine from upstreaming turbines [13,14]. In a wind farm, wake effect causes less power production because of the deficits in the wind speed, in addition to more maintenance cost because of the vibration and wear of turbines. Consequently, layout of a wind farm (WFL) by locating wind turbines in an optimal fashion by reducing wake effects among the located turbines becomes extremely important to maximize power production and minimize cost per unit of power produced.

WFL problem was first examined by Mosetti et al. [2] in 1994. They developed a genetic algorithm to find the total number and locations of wind turbines in a 10*x*10 grid of possible turbine locations to maximize the ratio of power to installation cost. They used Jensen's wake decay model [11] to analyze the wake effect considering several example cases of various wind speeds and directions. An improved genetic algorithm proposed by Grady et al. [3] achieved better results than Mossetti et al. [2] on the same example cases utilizing the same wake effect model. Marmidis et al. [4] used Monte Carlo simulation for WFL problem using Jensen's wake decay model while subsequent studies by Emami and Noghreh [19], Gonzales et al. [5], Zhang et al. [22], Shakoor et al. [29] as well as Mittal [20] presented evaluative algorithms to the problem. Pookpunt and Ongsakul [6], Wan et al. [23] and Rahmani et al. [21] proposed a binary particle swarm optimization method to optimize wind turbine layout. Eroğlu and Seçkiner presented two different studies where ant colony algorithm [24] and particle filtering approach [18] models are used for WFL problem assuming

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https://doi.org/10.1016/j.renene.2018.09.085
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continuous space. For WFL problem with continuous space, also, Ozturk and Norman [25] presented a greedy heuristic. Meanwhile, Kusiak and Song [26] developed an evolutionary algorithm for the problem. A few mathematical programming approaches to WFL problem have been proposed in the literature since the nonlinearity of the wake effect is one of the main problems in the formulations as asserted in Samorani [7]. Pérez et al. [28] used a mathematical model for WFL where the initial random layout is generated using a heuristic method. Donovan [8] developed mixed-integer programming models based on vertex packing problem considering interactions between the pairs of wind turbines. Archer et al. [9] presented similar mixed-integer programming models but assumed the largest single wake effect on each turbine. Also, boundaries of the wind sector and geometric relationship between the turbines are considered with an interference coefficient. Turner et al. [10] proposed both quadratic-integer and linear-integer programming models for WFL. These models involve the multiple wake effects on each turbine using a matrix prepared a priori. The matrix, which is called interaction matrix, gives the multiple wake effects on each possible wind turbine location. Turner et al. [10] showed that the suggested linear-integer programming model superior to the existing methods on the sample cases presented in Mosetti et al. [2].

During the last two decades there exists an increasing interest in solving of WFL considering different aspects of the problem. Objective function to evaluate alternative layouts, such as maximization of the power or annual energy production (AEP), minimization of levelized cost of energy (LCOE) or cost per power unit, is one of the aspects. While Herbert-Acero et al. [32] reviewed these objective functions in detail, Pillai et al. [33] presented an application of full LCOE to a real offshore wind farm. Larsen et al. [34] developed TOPFARM as an optimization tool to WFL problem from a cost perspective including foundation cost, electrical grid and fatigue costs. Réthoré et al. [35] also presented a multi-fidelity implementation of TOPFARM to maximize financial output of the farm over its lifetime. Another important aspect in solving of WFL problem is the wake modeling approach which considerably impacts assessment of the objective function. There exists a variety of models, such as Jensen [11], Larsen [36,37], dynamic wake meandering [38], Ainslie Eddy-Viscosity [39,40], and Fuga [41], presented in the literature and/or used in commercial packages to compute wake effects in a wind farm. Pillai et al. [42], Göçmen et al. [43], and Shakoor et al. [27] give comprehensive surveys on these models and discuss the comparative advantages of the models. Among the existing wake models, Jensen's [11] wake model is a widely-used model in solving methods of WFL problem due to its simplicity, practicality, and robustness as reported in Shakoor et al. [27] and Göçmen et al. [43]. Additionally, this model has been used in several versions of the Wind Atlas Analysis and Application Program (WAsP) which have been used widely to estimate wind resources for wind farm calculations [31]. A comparative study given by Gaumond et al. [44], on the other hand, shows that Jensen model may under-predict power production of the first turbines of a given layout while overpredict that of the last turbines. Therefore, parameters used in the Jensen model should be selected carefully to provide more accurate estimations for large wind farms [44]. Several other issues, for instance, varying turbine types/heights, flat or complex terrain types, and variability of wind have been also taken into account in the related literature [45–47].

Proposed solving methods for WFL problem considering its different aspects are mostly heuristic algorithms such as genetic algorithm [2,3,5,20,22,26,29,48,49], ant colony [12,24], random search [50,51], particle swarm optimization [6,18,21,23,52], greedy search [25,53], and few are mathematical programming based methods [8–10,28]. Also, there are two main approaches to deal with the layout representation in both heuristic and mathematical programming based methods. The first approach assumes a discrete search space by discretizing terrain of the wind farm using a grid design. Each cell of the grid is assumed as a possible turbine location and therefore, a binary variable associated with each cell indicates absence or existence of a turbine. According to the other approach, the terrain is a continuous search space so that turbines can be located at any (x, y) coordinate in it. Since searching in a discrete space simplifies the modeling of WFL problem comparing with a continuous space, most of the studies in the literature use the discrete search space. Nevertheless, the studies on WFL such as Ozturk and Norman [25], Eroğlu and Seçkiner [24], Kusiak and Song [26], and Rivas et al. [56], which assume continuous space, have been increasing due to the relevance with the industry. Readers are also referred to comprehensive surveys on WFL problem reported by Tesauro et al. [54], Herbert-Acero et al. [32], and González et al. [55].

The review of WFL literature shows that it mostly consists of heuristic methods and a few mathematical programming methods because of the difficulties in solving WFL problem optimally. On the other hand, mathematical programming models may find sub-optimum or optimum layouts if a proper global optimization method is applied for solving, even it takes a long computer time. In this paper, a new nonlinear mathematical programming model, which has totally unimodularity property, is presented for WFL problem to maximize total power production and minimize cost of power. Due to the totally unimodularity property of the presented model, decision variables of turbine locations are guaranteed to be binary and there is no need to deal with integer optimization. Thus, we aim to contribute the literature of WFL by introducing a mathematical model which is relatively simple to solve. The model was tested on a suit of test problems considering different wind conditions to demonstrate its capability in real life applications. Additionally, it was shown that the proposed model yields better results in terms of both total power production and cost per power on the sample cases given in Mosetti et al. [2] compared to the existing methods in the related literature.

The paper continues with a preliminary background for the wake modeling adapted in this study in Section 2. The proposed nonlinear mathematical programming model is explained in Section 3. Section 4 gives the computational study to show performance of the model on a set of test problems available in the literature, and on a real case. In the last section, conclusions and possible future directions are discussed.

2. Wake modeling

In this study, Jensen's [11] wake model is utilized to compute wake effects in the mathematical model developed. Besides the advantages of Jensen model, we also aim to provide the same baseline in the comparative studies given in, since all the methods mentioned in these subsections utilize the same wake model. Jensen's [11] wake model is based on the distance behind the rotor and assumes a linear expanding wake. The model explained briefly below was also refined by Katic et al. [16] introducing wake merging.

According to Jensen's wake model, wind speed, u_{ij}, received by a turbine at position (i,j) is computed as given in equation (1) where vd_{ijps} is the velocity deficit in the wind speed due to the turbine located at (p,s) and u_0 is the ambient wind speed. Also, it is assumed that the terrain in which the turbines are located is flat. vd_{ijps} is calculated as given in equation (2) in terms of distance D_{ijps} between turbines at positions (i,j) and (p, s), rotor radius r, enlargement of the wake k, and axial induction factor a. Here, enlargement of the wake, k, describes how the wake breaks down respect to the growth in the width of wake through the downstream and axial induction factor, a, is used to estimate the axial force applied on the rotor of the turbine. In this study, parameters a and k are computed as given in Ref. [11]. Regarding the wake area of turbine at (p,s) and swept area of turbine at (i,j), equation (2) is extended to equation (3) [16]. According to this extension, if turbine (i,j) is completely in the wake of turbine (p,s), then $A_{ijps} = A_{ij}$, else A_{ijps} is the overlapping area between the swept area of turbine (i,j) and wake area of turbine (p,s). Calculation of the overlapping area can be found in detail in Gonzalez et al. [5].

$$u_{ij} = u_0\left(1 - vd_{ijps}\right) \tag{1}$$

$$vd_{ijps} = \frac{2 \cdot a}{\left(1 + \frac{k \cdot D_{ijps}}{r}\right)^2} \tag{2}$$

$$vd_{ijps} = \frac{2 \cdot a}{\left(1 + \frac{k \cdot D_{ijps}}{r}\right)^2} \cdot \frac{A_{ijps}}{A_{ij}} \tag{3}$$

When a turbine located at (i,j) is affected by more than one turbine's wake, multiple wake effects, $vdef_{ij}$, on this turbine is equal to sum of the squares of individual velocity deficits generated by each wake as given in equation (4) under the assumption of linear superposition of the squares of the velocity deficits [11]. Hence, the remaining velocity u_{ij} received by a turbine at (i,j) is calculated using equation (5).

$$vdef_{ij} = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{p=1}^{N}\sum_{s=1}^{N} vd_{ijps}} \tag{4}$$

$$u_{ij} = u_0 \cdot \left[1 - vdef_{ij}\right] \tag{5}$$

2.1. Dealing with the multiple wake effects

This subsection explains briefly the methodology suggested by Turner et al. [10] to incorporate multiple wake effects into a mathematical model avoiding the nonlinearity in the calculation of wake effects. The similar methodology is also adapted in the mathematical model developed in this study which is presented in Section 3. Distance between turbines at positions (i,j) and (p,s) is calculated by including the wind direction θ as given in equation (6) [12].

$$D_{ijps} = \left|\left(x_i - x_p\right)^* \cos(\theta) + \left(x_j - x_s\right)^* \sin(\theta)\right| \tag{6}$$

It is assumed that the terrain available for the wind farm is a grid of size NxN. An interaction matrix of size $(NxN)x(NxN)$ represents all possible multiple wake effects, that is, an entry of the interaction matrix at position $(i,j)x(p,s)$ gives $Vdef_{ij}$ computed in advance. Each possible turbine location has $J-1$ interaction between itself and other possible turbine locations where J is the size of turbine locations. Also, it is accepted that the turbines can turn to face at any given wind direction.

In addition, expected multiple wake effects, EVd_{ij}, are computed using equation (7) in case of multiple wind directions where W represents the set of possible wind directions and P_k gives the probability of wind blows from direction k for $k = 1, \ldots, W$. As assumed in Turner et al. [10], the kinetic energy deficits are accepted to be additive to compute the expected deficits.

$$EVd_{ij} = \sum_{k=1}^{W} P_k vd^k \tag{7}$$

3. Proposed nonlinear mathematical model for WFL problem

The proposed mathematical model in this study is based on the grid design of terrain such that each cell (i,j) of the grid with size NxN corresponds a possible turbine location where TN is the number of turbines to be placed in the wind farm. Decision variables of WFL problem, therefore, can be stated as follows:

$$x_{ij} = \begin{cases} 1, & \text{if there is a turbine at position (i,j) for } i,j = 1,\ldots,N \\ 0, & \text{otherwise} \end{cases}$$

The first objective function considered in this study is to maximize total power production. Power produced by an individual wind turbine (i,j) is given by equation (8) where η is turbine efficiency, ρ is air density, and A is cross-sectional area. The corresponding curve is taken from Mosetti et al. [2] as shown in Fig. 1. In equation (9), velocity deficits are incorporated into the calculation of power. In the case of multiple wind directions, velocity deficits in equations (8–9) are replaced by expected velocity deficits, Evd_{ijps}. Hence, total power produced by turbines located at positions (i,j) is maximized as given in equation (10). To include financial considerations, cost per power unit is also taken into consideration. Total cost function given in equation (11) was adapted from Mosetti et al. [2] since the function has been used widely in the related literature. Accordingly, the second objective function is defined in equation (12). Feasible solutions of WFL problem must satisfy turbine number constraint in equation (13) and binary constraints in equation (14). Turbine number, TN, is given a priori for the maximization objective function, while it is led to be unknown for the minimization objective function to find a cost efficient layout including the turbine number.

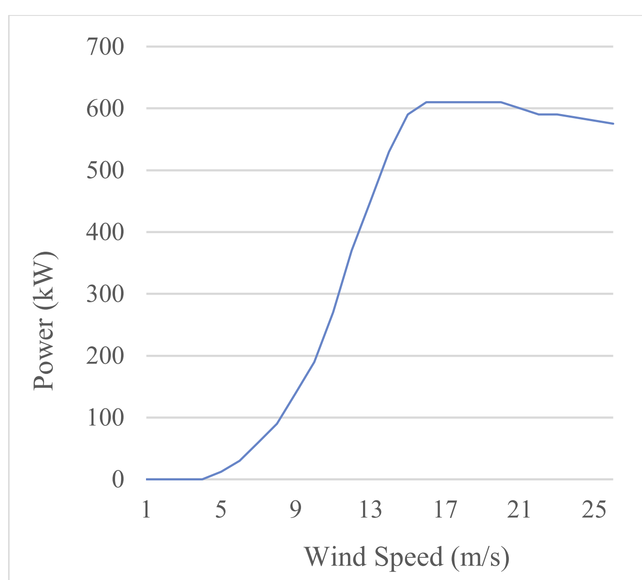

Fig. 1. The power curve of a wind turbine [2].

$$P_{ij} = \eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot u_{ij}^3 \tag{8}$$

$$P_{ij} = \eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot \left[u_0 \cdot \left[1 - \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{p=1}^{N} \sum_{s=1}^{N} vd_{ijps}} \right] \right]^3 \tag{9}$$

$$Max \sum_{i=1}^{N} \sum_{j=1}^{N} \eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot x_{ij} \cdot \left[u_0 \left[1 - \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{p=1}^{N} \sum_{s=1}^{N} x_{ps} \cdot vd_{ijps}} \right] \right]^3 \tag{10}$$

$$TC = TN \cdot \left(\frac{2}{3} + \frac{1}{3} e^{-0.00174.TN^2} \right) \tag{11}$$

$$Min \quad \frac{TN \cdot \left(\frac{2}{3} + \frac{1}{3} e^{-0.00174.TN^2} \right)}{\sum_{i=1}^{N} \sum_{j=1}^{N} \eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot x_{ij} \cdot \left[u_0 \left[1 - \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{p=1}^{N} \sum_{s=1}^{N} x_{ps} \cdot vd_{ijps}} \right] \right]^3} \tag{12}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N} x_{ij} \le TN \tag{13}$$

$$x_{ij} \in (0, 1) \qquad \forall i, j \tag{14}$$

There are two main difficulties in the solving of WFL problem: The first difficulty stems from the nonlinearity of the objective functions given in equations (10) and (12). To cope with the nonlinearity of multiple wake effects in the power function, the methodology explained in subsection 2.1 is used. Preparation of the multiple wake effects according to this methodology, in advance, facilitates the calculation of the power function, but both the objective functions remain nonlinear. It is obvious that any improvement in the layout will make the farm more productive for its whole lifetime since WFL problem is a long-term planning problem which is solved once and then applied permanently as the wind farm stands. Therefore, the proposed mathematical model in this study uses nonlinear functions of the two objectives in the purpose of producing more power, despite of the difficulty of nonlinearity.

The other difficulty in solving of WFL problem has resulted from the binary variables of decisions on turbine locations which makes WFL nonlinear integer programming problem. When the grid size N is 100, for instance, solution space consists of 2^{100} number of possible layouts. The problem has a huge search space which is difficult to search. On the other side, if the binary constraints in the nonlinear integer programming model are dropped by replacing equation (14) with the inequalities given in (15), the model becomes only a nonlinear programming model. The left-hand-side coefficients of all x_{ij} variables in each constraint defined by equations (13) and (15) can be represented in a $(1+NN)\text{x}NN$ matrix **B** as given below. The first row of matrix **B** shows coefficients of each x_{ij} in equation (13), remaining rows correspond to coefficients of each x_{ij} in each inequality of (15).

$$0 \le x_{ij} \le 1 \text{ for } \forall i, j \tag{15}$$

$$\mathbf{B} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

According to "totally unimodularity property", a mathematical model which has a totally unimodular matrix in its defining constraints generates integer solutions if right-hand-side values of these constraints are also integers. There exist three sufficient conditions to show a given matrix is totally unimodular [15]. The matrix **B** defined above meets these conditions as given follows, where b_{ij} is the entry in ith row and jth column of the matrix:

(i) Each coefficient $b_{ij} \in \{0, 1\}$ for all i, j.
(ii) Each column of **B** contains at most two nonzero coefficients, that is, $\sum_{i=1}^{N} b_{ij} \le 2$.
(iii) There exists a partition of (M_1, M_2) of the all rows of **B** such that each column j containing two nonzero coefficients satisfies $\sum_{i \in M_1} b_{ij} - \sum_{i \in M_2} b_{ij} = 0$. Clearly, if M_1 is led to contain only the first row which corresponds to the turbine number constraint and M_2 contains all the remaining rows, the third condition is also provided.

Therefore, matrix **B** of the proposed model guarantees that even constraints $x_{ij} \in (0, 1)$ are replaced with $0 \le x_{ij} \le 1$ for $\forall i, j$, a feasible layout obtained from this model must also satisfy the binary requirements. Thus, the proposed nonlinear model (called NLM) in this study which consists of constraints given by equations (13) and (15) is relatively simpler to solve than the nonlinear integer model in which the binary requirements are stipulated.

4. Computational results

In order to show the performance of NLM, a set of test problems

Table 1
Input parameters for the cases.

Rotor radius (r)	20 m
Hub height (z_0)	60 m
Grid size	100 square cells
Cell size	$10r_0$ (200 m × 200 m)
Thrust coefficient (C_T)	0.88
Enlargement of the wake (k)	0.1
Wind turbine efficiency (η)	40%
Air density (ρ)	1.2
Cross-sectional area (A)	πr^2
Power (P_{ij})	$\left(\frac{1}{3}\right) u_{ij}^3$

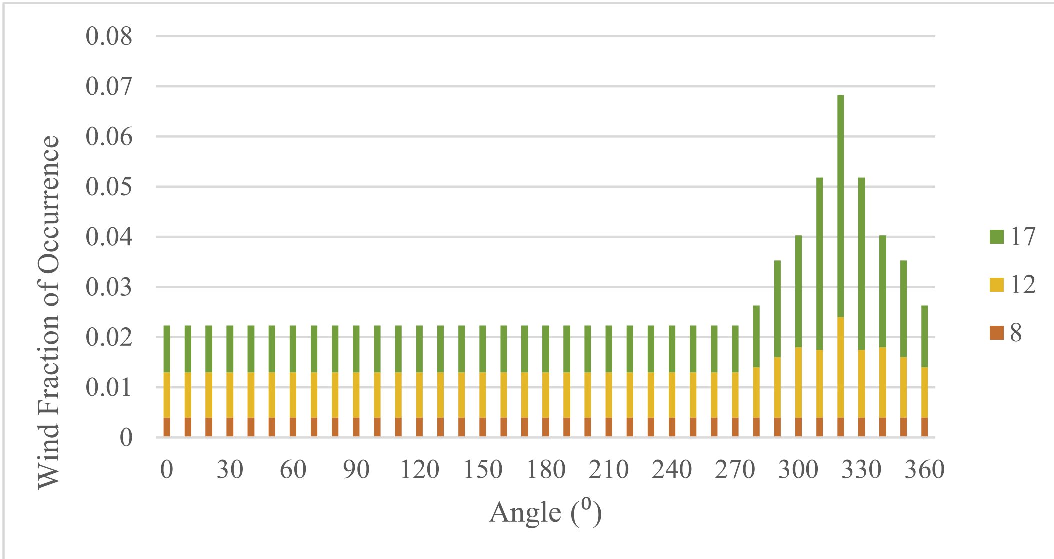

Fig. 2. Variable wind direction and variable wind speed of case IV.

Table 2
Performance of NLM model with the objective function of cost per power.

NLM			
Case	TN	Power (kW)	Cost/Power
I	30	16148.71	0.0014
II	32	14378.62	0.0016
III	36	16483.88	0.0015
IV	36	25369.43	0.0010

was created for four different cases given below taking into account the parameters in Table 1. Parameter values in the table are also suggested and widely used in the related literature including the researches mentioned in subsection 4.3. Therefore, we aim to provide the same baseline for the comparative studies given in the following subsections. For each case, additionally, the interaction matrix of velocity deficits was created in advance as explained in subsection 2.1 assuming the terrain is a grid of size 10×10.

(I) : one wind direction from north to south with constant wind speed of 12 m/s,
(II) : 8 wind directions with equal probabilities of occurrence with constant wind speed of 12 m/s,
(III) : 36 wind directions with equal probabilities of occurrence with constant wind speed of 12 m/s,
(IV) : 36 wind directions with unequal probabilities and variable wind speed of 8 m/s, 12 m/s, and 17 m/s where the fraction of occurrence for each angle at each wind speed is illustrated in Fig. 2 [2].

In the next subsection, the performance of NLM model is represented considering the objective function is the cost of power. In subsection 4.2, performance of NLM to maximize the total power function for given number of turbines is compared with that of the quadratic integer model (QIM) developed by Turner et al. [10]. Additionally, in subsection 4.3, NLM is compared with other solution methods existing in the literature on several benchmark problems.

LINGO software package is a comprehensive tool designed to make building and solving linear, nonlinear, and integer mathematical models developed in any application field. Because of several benefits of LINGO such as easy model expression, convenient data management, and powerful solvers, it was selected to solve NLM. Since NLM contains nonlinear objective function, the proper solver of LINGO is global optimization solver which utilizes methods of range bounding and range reduction within a branch and bound framework [30]. Global optimization solver of LINGO employs multi-starting using a different initial solution each time and reports the best solution. Therefore, the following subsections report the best solutions obtained from NLM and the best solutions available in the literature for the cases defined above. The runs were executed on a 1.70 GHz Intel Core i5 notebook with 6 GB of RAM. An upper limit of 2-h on the runtime was set since the pre-experiments showed that good solutions already can be obtained within two hours using NLM.

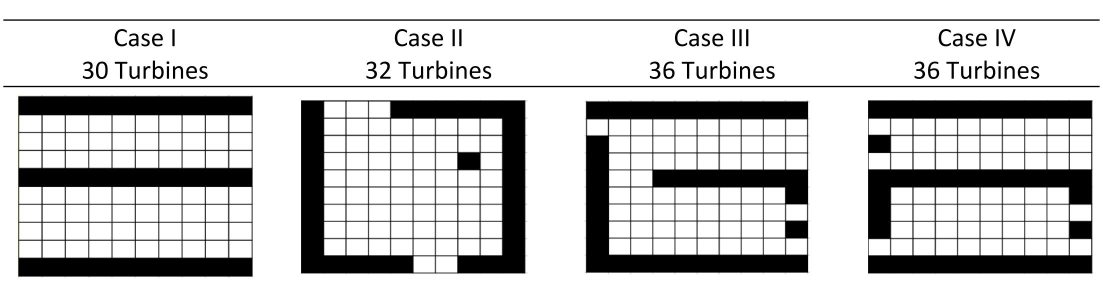

Fig. 3. NLM layouts with the objective function of cost per power.

Table 3
Comparative results of cost per power for case I, III, and IV.

Studies	Case (I)		Case (III)		Case (IV)	
	TN	Cost/Power	TN	Cost/Power	TN	Cost/Power
Mosetti et al. [2]	26	0.00157	19	0.0018	15	0.0036
Rahmani et al. [21]	26	0.00154	-[a]	–	–	–
Marmadis et al. [4]	29	0.00142	–	–	–	–
Grady et al. [3]	30	0.00154	39	0.0016	39	**0.0008**
Gonzalez et al. [5]	30	0.00154	39	**0.0015**	–	–
Zhang et al. [22]	30	0.00154	39	**0.0015**	39	**0.0008**
Marmadis et al. [4]	32	0.00141	–	–	–	–
Mittal [20]	32	0.00202	38	**0.0015**	41	**0.0008**
Shakoor et al. [29]	32	0.00153	–	–	–	–
Pookpunt and Ongsakul [6]	30	0.00154	35	0.0017	46	**0.0008**
NLM	30	**0.00136**	**36**	**0.0015**	**36**	0.0010

[a] Not available in the respective study.

4.1. Performance of NLM on minimization of cost of power

Solving of NLM, in which the objective function is to minimize the cost of power, results in the number of turbines, cost/power, and total power as presented in Table 2 for each of the four cases. Fig. 3 illustrates these cost-efficient wind farm layouts. The worst cost/power is obtained under the condition of case II, whereas the best occurs under case IV. Results show that NLM tends to place more turbines as the wind speed and possible wind directions increase.

Table 3 provides a comparison of the solutions obtained from NLM with the solutions taken from the previous studies of related literature. In Table 3, all the studies aim the minimization of cost per power and the numerical values of cost/power are taken from the respective articles. As seen from the table, the different studies suggest different number of turbines and thus, different cost/power even for the same case. NLM outperforms other studies in case I in terms of cost/power, while NLM, Gonzalez et al. [5], Mittal [20] and Zhang et al. [22] generate the same best solution in case III. For case IV, cost/power generated by NLM is quite close to the best, which is 8×10^{-4}, found by Grady et al. [3], Pookpunt and Ongsakul [6], Mittal [20] and Zhang et al. [22].

4.2. Comparison of NLM with QIM

QIM model developed by Turner et al. [10] was re-implemented in this study under the same conditions with NLM (that is, using the same data, hardware, solver, and runtime limit). Table 4 shows the total power and cost/power results obtained by NLM and QIM for varying number of turbines in each of the four cases. NLM has better performance than QIM for the instances with 30 and more turbines in case I. For the other cases, NLM generates better layouts comparing QIM in terms of both power production and cost/power for each number of turbines. Fig. 4 and Fig. 5 represent the wind farm layouts of NLM and QIM models for the turbine numbers from 10 to 50 under case IV, respectively, as examples. Results in Table 4 show that the performance of NLM does not deteriorate under different wind conditions (i.e., cases) comparing QIM.

Table 4
The performance results of NLM and QIM.

	TN	QIM Power (kW)	QIM Cost/Power	NLM Power (kW)	NLM Cost/Power
Case I	10	5760	**0.00164**	5760	**0.00164**
	20	11364.97	**0.00147**	11364.97	**0.00147**
	30	13976.48	0.00158	16163.17	**0.00137**
	40	16390.31	0.00168	19609.62	**0.00140**
	50	16302.32	0.00206	22644.51	**0.00148**
	TN	QIM Power (kW)	QIM Cost/Power	NLM Power (kW)	NLM Cost/Power
Case II	10	5076.36	0.00187	5358.10	**0.00177**
	20	9050.80	0.00184	10007.37	**0.00166**
	30	12465.47	0.00177	13706.81	**0.00161**
	40	15963.21	0.00172	16916.04	**0.00163**
	50	18283.37	0.00183	19706.83	**0.00170**
	TN	QIM Power (kW)	QIM Cost/Power	NLM Power (kW)	NLM Cost/Power
Case III	10	5378.24	0.00176	5418.89	**0.00175**
	20	10034.64	0.00166	10165.74	**0.00164**
	30	13982.22	0.00158	14253.38	**0.00155**
	40	17751.59	0.00155	17863.68	**0.00154**
	50	17800.54	0.00188	20992.21	**0.00160**
	TN	QIM Power (kW)	QIM Cost/Power	NLM Power (kW)	NLM Cost/Power
Case IV	10	8322.15	**0.00114**	8322.15	**0.00114**
	20	15471.27	0.00108	15710.60	**0.00106**
	30	21699.40	0.00102	21984.69	**0.00100**
	40	27398.42	0.00100	27438.79	**0.00100**
	50	32249.62	0.00104	32270.42	**0.00104**

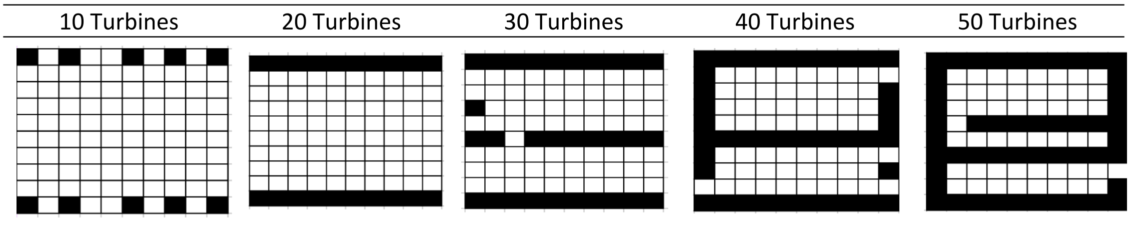

Fig. 4. NLM layouts for case (IV).

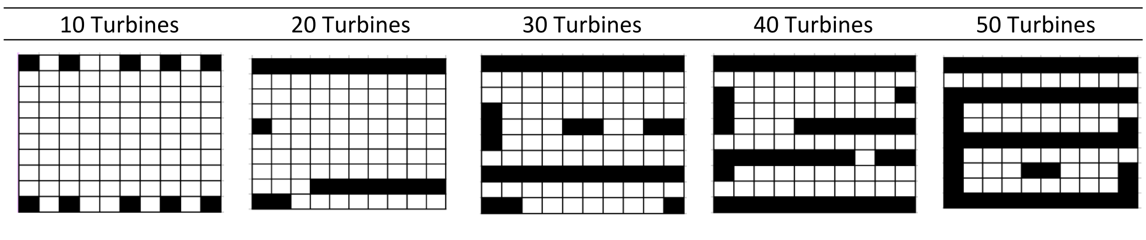

Fig. 5. QIM layouts for case (IV).

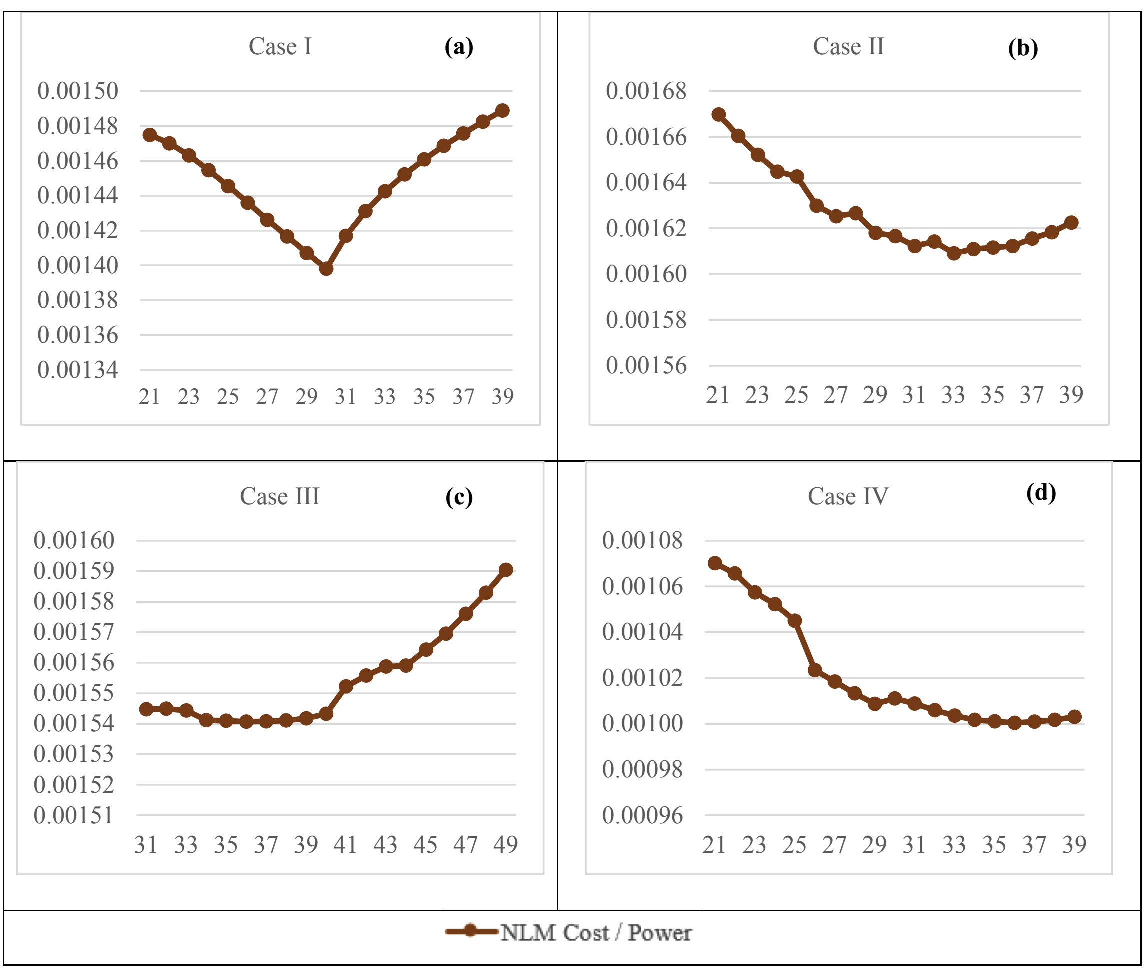

Fig. 6. Sensitivity analysis (a) Case I (b) Case II (c) Case III (d) Case IV.

We also carried out a sensitivity analysis to make a precise determination of the number of turbines for each case. For this purpose, the number of turbines was increased by one in the vicinity of the minimum cost/power given in Table 4. As depicted in

Table 5
Case (I) results.

TN	Model	Total Power (kW)	Cost/Power
26	Mosetti et al. [2]	10465.58	0.00191
	Turner et al. [10]	**14163.42**	**0.00141**
	Rahmani et al. [21]	10192.09	0.00196
	NLM	**14163.42**	**0.00141**
29	Marmadis et al. [4]	10886.16	0.00198
	NLM	**15690.17**	**0.00137**
30	Grady et al. [3]	**16163.17**	**0.00137**
	Turner et al. [10]	**16163.17**	**0.00137**
	Emami and Noghreh [19]	**16163.17**	**0.00137**
	Gonzalez et al. [5]	**16163.17**	**0.00137**
	Zhang et al. [22]	**16163.17**	**0.00137**
	NLM	**16163.17**	**0.00137**
32	Marmadis et al. [4]	12008.43	0.00193
	Mittal [20]	16014.18	0.00144
	Shakoor et al. [29]	13636.39	0.00170
	NLM	**16831.29**	**0.00137**

Table 6
Case (III) results.

TN	Model	Total Power (kW)	Cost/Power
19	Mosetti et al. [2]	9104.37	0.00176
	Turner et al. [10]	9378.80	0.00171
	NLM	**9707.76**	**0.00165**
35	Pookpunt and Ongsakul [6]	15847.65	0.00156
	NLM	**16134.55**	**0.00153**
39	Grady et al. [3]	16464.25	0.00164
	Turner et al. [10]	16197.69	0.00166
	Gonzalez et al. [5]	16464.25	0.00164
	Zhang et al. [22]	16381.47	0.00164
	NLM	**17533.21**	**0.00154**
40	Zhang et al. [22]	16683.12	0.00165
	NLM	**17863.68**	**0.00154**

Fig. 6 from (a) to (d), cost/power is minimized at 30, 32, 36, and 36 turbines for cases I, II, III, and IV, respectively.

4.3. Comparison of NLM with other existing methods

In this subsection, the performance of NLM is compared with other existing methods, which assume discrete design of terrain and utilize Jensen's wake model, in addition to the study of Turner et al. [10]. Studies considered in this subsection have reported the best layouts for different number of wind turbines under case I, case III, or case IV. These best layouts are taken directly from the respective articles and corresponding total power is computed in this study to make a comparison with NLM. Thus, the results only for the instances, which the best layouts are available in the existing literature, are given in Tables 5–7.

Table 7
Case (IV) results.

TN	Model	Total Power (kW)	Cost/Power
15	Mosetti et al. [2]	11201.93	0.00113
15	Turner et al. [10]	11704.81	0.00108
15	NLM	**12103.02**	**0.00105**
28	Emami and Noghreh [19]	18438.94	0.00107
28	NLM	**20776.31**	**0.00095**
39	Grady et al. [3]	25550.14	0.00108
39	Turner et al. [10]	24727.14	0.00111
39	NLM	**26932.28**	**0.00100**
46	Pookpunt and Ongsakul [6]	28976.28	0.00110
46	NLM	**30424.29**	**0.00104**

Table 5 shows the calculated total powers of the best layouts and corresponding cost of power for each given number of turbines under case I. For 26 of the number of turbines, the layout found by NLM and the layout given in Turner et al. [10] generate the highest total power. NLM improves the results of Mosetti et al. [2] and Rahmani et al. [21] by 35.33% and 38.96%, respectively. NLM is also superior to the Monte Carlo simulation of Marmadis et al. [4] for 29 turbines. All the methods generate the same layout for 30 wind turbines resulting the same total power. NLM strongly outperforms other methods for 32 turbines yielding 40.16%, 5.10%, and 23.43% improvements in total power comparing to Marmadis et al. [4], Mittal [20], and Shakooer et al. [29], respectively. The wind farm layouts, which are found by NLM and reported in the literature, are also illustrated in Fig. 7 for 26, 29, 30 and 32 turbines.

Total power and cost/power results, under case III, are given in Table 6 for the different number of turbines reported by the respective studies. As seen from the table, layouts generated by NLM are superior to that of other methods by generating the highest total power and the lowest cost/power for each given number of turbines. The obtained wind farm layouts are also shown in Fig. 8 for 19, 35, 39 and 40 turbines.

Table 7 shows the results of total power and cost per power for the reported number of turbines by the associated studies under the conditions of case IV. For each given number of turbines, NLM has better performance in terms of power generation in addition to yielding the minimum of cost per power among all the reported studies in the table. The obtained wind farm layouts including the layouts of previous studies for 15, 28, 39 and 46 turbines are shown in Fig. 9.

Consequently, Figs. 7–9 indicate that the layouts found by NLM tend to be structured in arrays while the other layouts, in general, are scattered. Also, the layouts obtained by NLM are more cost-efficient than most of the layouts available in the literature as seen in Tables 5–7. This result shows that NLM can be used for solving of WFL problems to maximize total power and/or minimize the cost of power.

4.4. Application of NLM to a real case

In the previous sections, the proposed mathematical model NLM and its effectiveness are discussed compared to other solution methods existing in the literature on several benchmark problems. In this subsection, an example of the famous Danish Middelgrunden offshore wind farm is given to demonstrate the applicability of NLM to real life problems.

Middelgrunden wind farm is composed of 20 2 MW wind turbines with a hub height of 64 m and a rotor diameter of 76 m in a curved arc-like layout with a mutual turbine spacing of 2.3 times the diameter [57–60]. All input parameters for Middelgrunden case including site wind climate and wind turbine information are taken from the TOPFARM project [34,35,57,58] and given in Table 8.

NLM was applied to Middelgrunden wind farm considering two objective functions separately: maximization of total power production to re-layout currently available 20 turbines and minimization of cost per power to investigate a better cost-efficient wind farm for Middelgrunden. To apply NLM, firstly, terrain of Middelgrunden wind farm was represented as a grid of 88 cells (i.e., feasible turbine positions) where size of each cell is 2.3 times of the turbine diameter. Fig. 10a gives the proposed grid design. Global solver of LINGO worked NLM out just in seconds for each of the two objective functions. Maximizing the total power produced by existing twenty turbines and minimizing the cost of total power resulted in the same layout as illustrated in Fig. 10b.

The layout found by NLM was compared to the existing layout of Middelgrunden wind farm as given in Table 9. Table 9 also includes

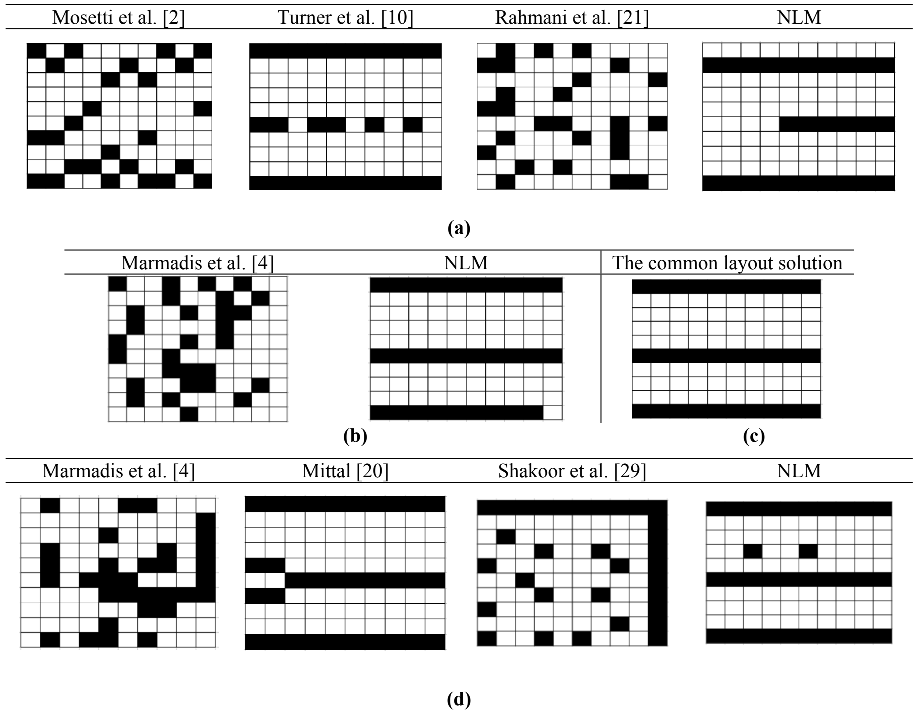

Fig. 7. Layouts for case (I) (a) 26 turbines (b) 29 turbines (c) 30 turbines (d) 32 turbines.

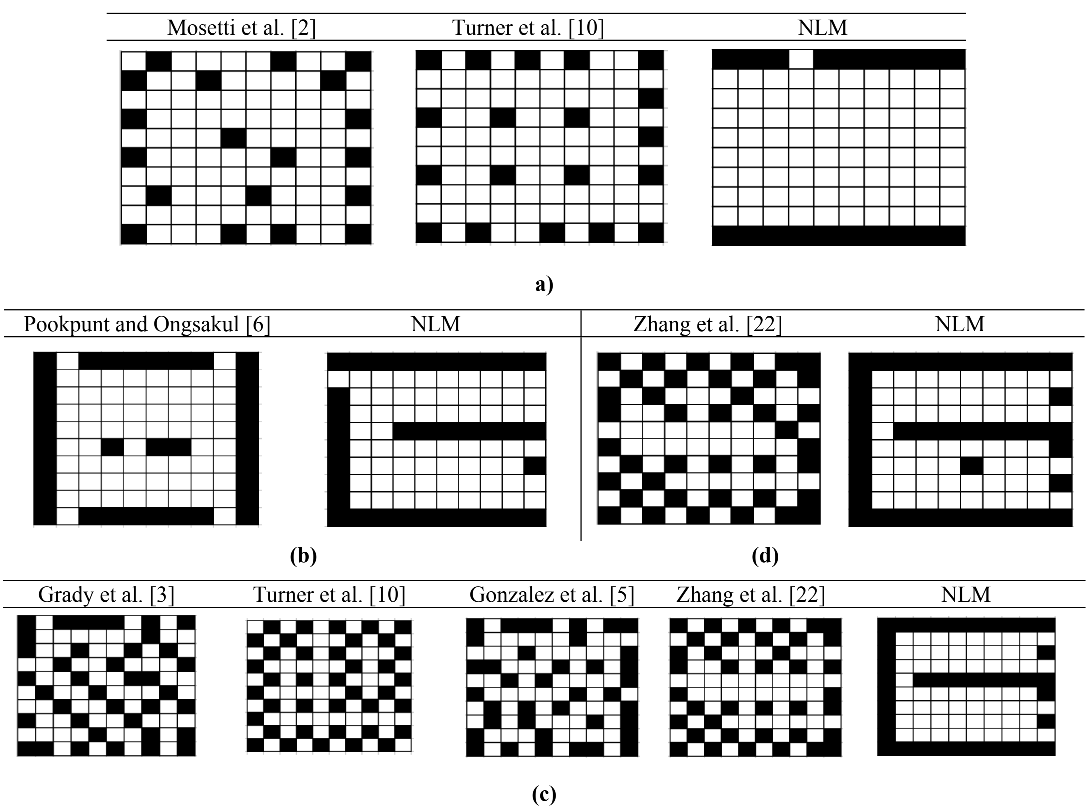

Fig. 8. Layouts for Case (III) (a) 19 turbines (b) 35 turbines (c) 39 turbines (d) 40 turbines.

the results of research carried out by Pillai et al. [33] and the results of TOPFARM project carried out by Larsen et al. [34] on the Middelgrunden case. Results in the table which correspond to the studies in Refs. [33] and [34] were obtained by converting the reported layouts in the respective studies into the grid design as given in Fig. 10c, d, and 10e. Pillai et al. [33] developed an evaluation tool

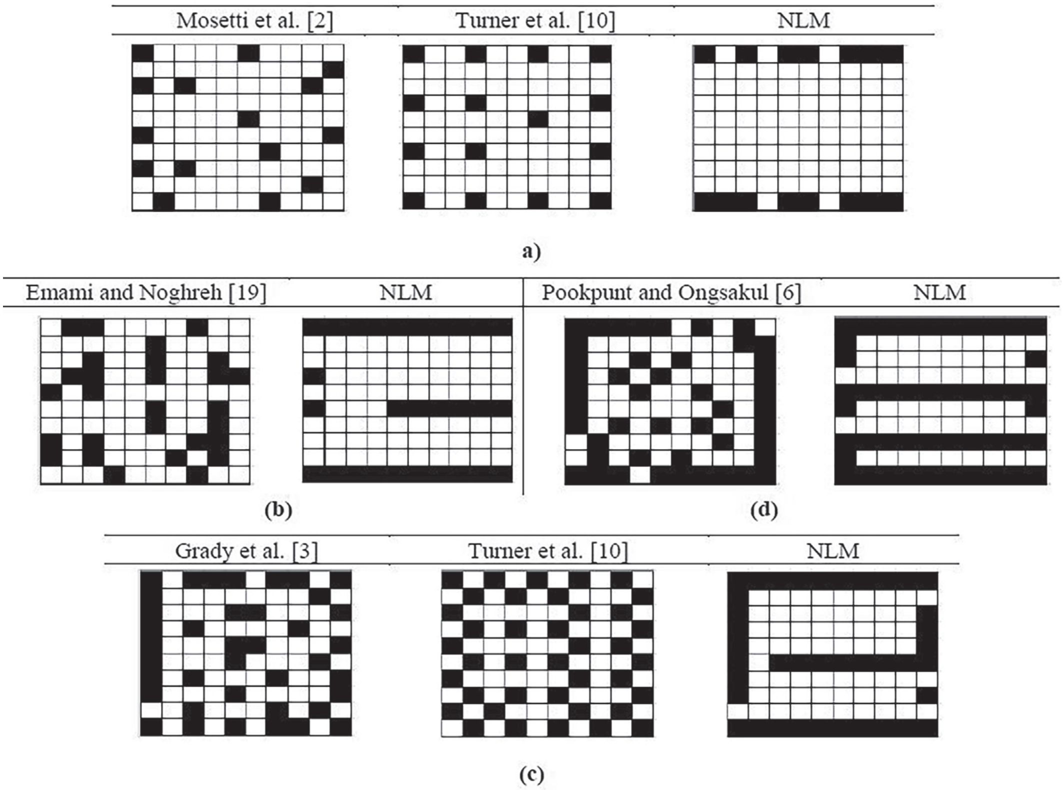

Fig. 9. Layouts for Case (IV) (a) 15 turbines (b) 28 turbines (c) 39 turbines (d) 46 turbines.

Table 8
Input parameters for the Middelgrunden offshore wind farm layout case.

Rotor radius (r)	38 m
Hub height (z_0)	64 m
Average wind speed (u_0)	7.2 m/s
Grid size	100 square cells
Cell size	180 m × 180 m
Wind turbine efficiency (η)	40%
Air density (ρ)	1.2
Cross-sectional area (A)	πr^2
Power (P_{ij})	$\eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot u_{ij}^3$
Wind Direction Degree	[0 30 60 90 120 150 180 210 240 270 300 330]
Wind Direction Wind Speed	[7.54 6.77 6.86 7.27 8.02 7.44 7.34 6.74 6.87 7.07 6.76 5.92]

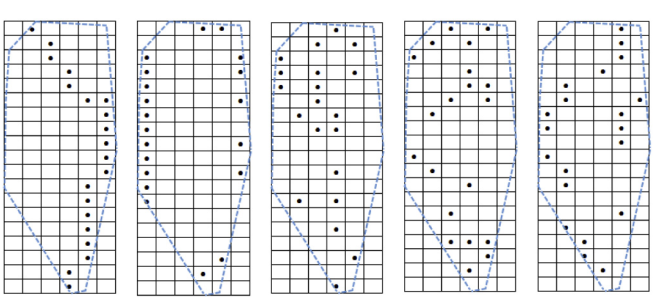

Fig. 10. (a) Representation of the existing Middelgrunden wind farm in the grid design (b) Layout obtained by NLM for both the objectives of maximizing total power and minimizing cost per power (c) Layout obtained from Pillai et al. [33] using GA-binary optimizer (d) Layout obtained from Pillai et al. [33] using PSO-binary optimizer (e) Layout of Middelgrunden obtained from Larsen et al. [34].

Table 9
Middelgrunden offshore wind farm case results.

Case	TN	Power (kW)	Cost/Power
Middelgrunden	20	4087.30533	0.00408
Pillai et al. [33] (GA-binary)	20	4567.83445	0.00365
Pillai et al. [33] (PSO-binary)	20	4393.89796	0.00379
Larsen et al. [34]	20	4705.47642	0.00354
NLM	20	5728.41974	0.00291

to estimate the lifetime cost, energy production, and levelized cost of energy including the electrical infrastructure for the Middelgrunden. The authors also proposed a genetic algorithm (GA) and a particle swarm optimization algorithm (PSO) for the WFL problem of Middelgrunden. Although each of the two algorithms were applied considering binary, continuous, and array modes in Ref. [33], Table 9 gives only the results of binary mode since NLM is also based on the binary representation as explained in Section 3. In the TOPFARM project, another optimization tool for WFL problem was introduced to obtain an optimal economic energy production during the lifetime of a wind farm considering capital costs, operation and maintenance costs and costs of fatigues in components. In the project, a multi-fidelity optimization approach was proposed which uses a global optimization algorithm considering simplified cost functions and a gradient based optimization algorithm considering more complex costs functions. Results in Table 9 show that the layout generated by NLM is superior to the other layouts in terms of both maximum power and minimum of cost per power. On the other side, the capital investment cost functions which are taken into consideration in Refs. [33] and [34] include also cost of electrical infrastructure besides other cost items. Therefore, results in Table 9 may also indicate the effect of avoiding from cost of electrical cabling on the power production.

5. Conclusion

In the present study, a new nonlinear mathematical model is presented to solve WFL problem for both maximization of total power production and minimization of cost per power under the multiple wake effects. Multiple wake effects are incorporated to the proposed model calculating in advance according to the Jensen's wake decay model. Because of the difficulty in nonlinear calculation of both power function, and also binary decision variables of turbine positions, most of the existing studies in the literature are based on heuristic methods. On the other hand, any improvement in the layout of a wind farm which results in better performance will be permanent through the lifetime of wind farm. Therefore, there are rooms to investigate mathematical programming models further in order to design more effective wind farms. The proposed mathematical model in this study eliminates the binary variables of turbines since it has totally unimodularity property, but uses nonlinear objective functions. By means of totally unimodularity, relaxation of the binary variables makes the proposed model relatively simpler to solve than mathematical models which are both integer and nonlinear. The proposed nonlinear model was run allowing a limited run time under varying wind conditions to maximize total power generation for a given number of turbines, and also to minimize the cost of power for an unknown number of turbines. Because of both the limited run time and the nonlinearity in the objective functions, solutions obtained from the model using global optimization are sub-optimal solutions. However, it was observed that solutions obtained from NLM on the test cases are better compared to the other methods proposed previously in the literature of WFL in terms of both total power generation and cost of power. Additionally, quality of the presented solutions remains better comparatively even the wind condition is changed in terms of both speed and direction. Finally, NLM was implemented to re-layout a real wind farm in Middelgrunden to investigate existence of a better layout. Indeed, the layouts generated by NLM were found superior to the current layout providing more total power production and less cost of power. This result encourages us to use NLM in solving of WFL problems.

As a future study, we are planning to extend the presented mathematical model by including the design of cable connection problem which is an important part in the investment cost of a wind farm. Since the problem of both layout of turbines and decision of cable connections among turbines is hard to optimize, mathematical model based approximate solutions will be investigated.

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