Computing Near-Optimal Array Cable Layouts for Offshore Wind Farms, including Cable Choice

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Abstract

To harvest the generated power, the turbines of an offshore wind farm are connected to an electrical transformer by cable routes. Typical cable layouts use two cable types distinguished by price and capacity: High capacity is expensive. This work presents a heuristic for computing near-optimal layouts based on the Clarke and Wright savings heuristic for vehicle routing, and the layouts it computes for two real-life offshore wind farms. The computed layouts are 6% more expensive than the optimal layouts, and on average 5% cheaper than the actually installed layouts.

Keywords: Offshore wind farm array cable layout, Intermodal transportation, Savings heuristic

1 Introduction

Offshore wind farms are rapidly gaining importance as power stations. The European Wind Energy Association predicts installed capacity in Europe to rise from currently about 4 GW to 150 GW by 2030 [4]. In order to harvest the generated power, all turbines are connected by array cable to an (on- or offshore) electrical transformer. Subsea cable, and its installation and maintenance, is very expensive. Therefore, minimizing the cost of an offshore wind farm's cable layout significantly reduces the cost of power production.

The array cable layout problem is defined as follows [5]: Given turbine and transformer positions, and (typically two) cable types distinguished by cost and capacity in number of turbines, find a set of cable routes minimizing the total cable cost, connecting every turbine to a transformer, not exceeding cable capacity, and such that cables do not cross each other.

If there is only one cable type available, then the problem amounts to the well-known Open Vehicle Routing Problem (OVRP) [10] with unit demands and additional planarity constraints. OVRP is NP-hard [9].

Typical cable layouts use two cable types, which are distinguished by capacity and cost: The higher a cable's capacity, the more expensive it is. Figure 1 shows the layouts installed at Barrow [1] and Sheringham Shoal [2] offshore wind farms, which comprise 30 and 88 turbines, and one and two transformers, respectively. In both farms, two cable types with capacities five (solid lines) and eight (dashed lines) are used.

The availability of several cable types allows for increasing a cable route's capacity at the turbines on a cable. Thus, finding the optimal cable layout is an intermodal

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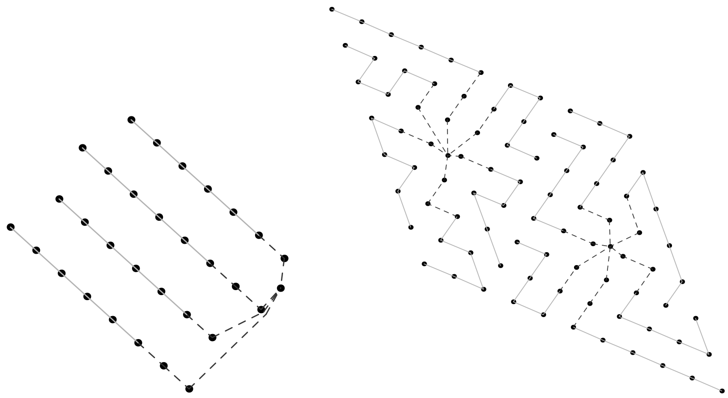


(a) Barrow (b) Sheringham Shoal

Figure 1: Layouts of two Offshore Wind Farms

transportation problem as defined in [7]. Research on intermodal transportation has mainly focused on freight transportation, and problem characteristics typically include decisions on schedules and terminal types (for example, for storage and consolidation). For offshore wind farms, decisions are restricted to identifying the cheapest cable layout.

For real-word offshore wind farms, optimal cable layouts can be found using mathematical programming. However, the computation can take several minutes [5]. For finding the best positions for the turbines in an offshore wind farm, many positions need to be computationally evaluated. For example, TopFarm, the to-date probably most sophisticated tool for finding the best turbine positions, evaluates more than 1000 turbine position configurations [11]. Therefore, fast heuristics computing near-optimal solutions are of high interest.

In [5], the Clarke and Wright savings heuristic [6] for vehicle routing is adapted to the POS1 heuristic for the array cable layout problem with only one cable type. It computes layouts only 2.4% more expensive than the optimal layouts, in less than 0.06 seconds. In the following, the POS1 heuristic is adapted to choice of two cable types.

2 The Cable Choice Savings Heuristic

Given are two cable types ("*cheap*" and "*expensive*") with capacities $C^0 < C^1$ and costs $c^0_{ij} < c^1_{ij}$ for every direct connection $i - j$ between two objects (turbines or transformers) i and j in an offshore wind farm.

The idea of the savings heuristics is to start with initial cable routes of the form $i - t_i$ connecting every turbine i to the transformer t_i nearest to i, and then iteratively decrease the cost of the layout by *merging* two cables routes $i_1 - i_2 - \ldots - i_h - t_{i_h}$ and $j_1 - j_2 - \ldots - j_k - t_{j_k}$ into $i_1 - i_2 - \ldots - i_h - j_1 - j_2 - \ldots - j_k - t_{j_k}$, provided that the resulting cable route is feasible, that is, $h + k \leq C^1$, and the connection $i_h - j_1$ does not cross any other connections of the incumbent layout. The saving s_{i_h,j_1} achieved by this merge is calculated as follows:

If $h + k \leq C^0$, then the resulting cable route consists only of cheap connections, and $s_{i_h,j_1} = c^0_{i_h,t_{i_h}} - c^0_{i_h,j_1}$.

If $h > C^0$, then merging results in expensive connections on the cable segment $i_{C^0+1} - \ldots - t_{j_k}$. Since the cable segment $i_{C^0+1} - \ldots - t_{i_h}$ already is expensive, as well as, if $k > C^0$, the segment $j_{C^0+1} - \ldots - t_{j_k}$, the saving in the case $h > C^0$ is

$$s_{i_h,j_1} = c^1_{i_h,t_{i_h}} - c^1_{i_h,j_1} - \sum_{\ell=1}^{\min\{C^0,k\}} c^1_{j_\ell,j_{\ell+1}} - c^0_{j_\ell,j_{\ell+1}}$$

If $h \leq C^0$ and $h+k > C^0$, then merging results in a cable route with the $h+k-C^0$ connections closest to t_{j_k} being expensive. They start at turbine j_ℓ with index $\ell = k+1-(h+k-C^0) = 1+C^0-h$. Accordingly, the saving in this case is

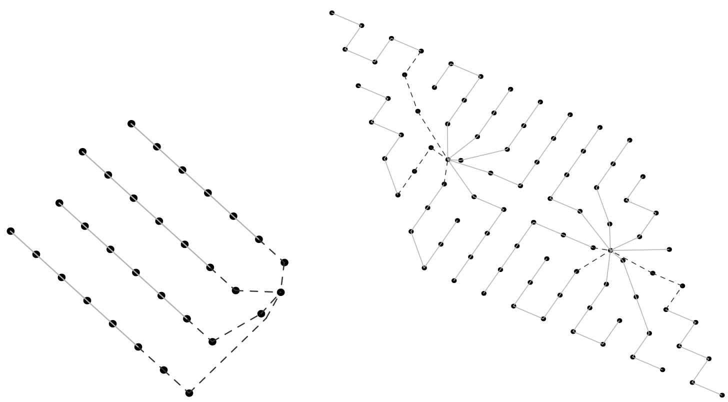
$$s_{i_h,j_1} = c^0_{i_h,t_{i_h}} - c^0_{i_h,j_1} - \sum_{\ell=1+C^0-h}^{\min\{C^0,k\}} c^1_{j_\ell,j_{\ell+1}} - c^0_{j_\ell,j_{\ell+1}}$$

The heuristic iteratively executes the merge yielding the largest positive saving and a feasible layout (without cable crossings and not exceeding the maximum cable capacity).

Finally, the local search heuristic RouteOpt [5] is applied to the cheap segments of the layout output by the savings heuristic.

3 Computational Results for Barrow and Sheringham Shoal

The two cables types installed at Barrow offshore wind farm have diameters 120mm and 300mm [1], which implies $c^0 = 80\frac{€}{m}$ and $c^1 = 140\frac{€}{m}$ [8]. The two cables types installed at Sheringham Shoal offshore wind farm have diameters 185mm and 400mm [3], which implies $c^0 = 110\frac{€}{m}$ and $c^1 = 180\frac{€}{m}$ [8]. For both offshore wind farms, $C^0 = 5$ and $C^1 = 8$. The layouts computed by the cable choice savings heuristic are shown in Fig. 2. They are 2% and 8% cheaper than the actually installed layouts at Barrow and Sheringham Shoal, respectively. For both farms, they are 6% more expensive than the optimal layouts computed in [5]. They are for comparison shown in Fig. 3.



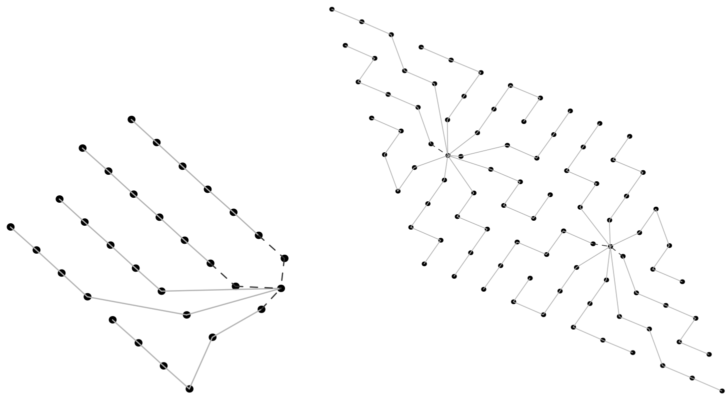
(a) Barrow (b) Sheringham Shoal

Figure 2: Layouts computed by the Savings Heuristic

4 Conclusions

We have shown how the savings heuristic POS1 [5] can be adapted to finding near-optimal layouts with two cable types.

We are currently developing methods for several extensions of finding the optimal cable layout , including finding the optimal transformer positions, and, in cooperation with major offshore wind farm developers, on more realistic layout models, for example including power loss. For these extensions, we develop both exact and heuristic methods.



(a) Barrow (b) Sheringham Shoal

Figure 3: Optimal Layouts

References

[1] http://www.bowind.co.uk/pdf/Barrow_coordinates.pdf.

[2] http://www.scira.co.uk/construction/foundationsmap.php.

[3] http://www.lorc.dk/offshore-wind-farms-map/sheringham-shoal.

[4] A. Arapogianni, J. Moccia, D. Williams, and J. Phillips. Wind in our Sails. Technical report, European Wind Energy Association, 2011.

[5] J. Bauer and J. Lysgaard. The Offshore Wind Farm Array Cable Layout Problem – A Planar Open Vehicle Routing Problem. Under revision for resubmission to the *Journal of the Operational Research Society*, 2013.

[6] G. Clarke and J.W. Wright. Scheduling of vehicles from a central depot to a number of delivery points. *Operations research*, 12(4):568–581, 1964.

[7] T.C. Crainic and K.H. Kim. Intermodal Transportation. In Cynthia Barnhart and Gilbert Laporte, editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, pages 467 – 537. Elsevier, 2007.

[8] T. Fosse. Optimizing the Infield Cable Layout in Offshore Wind Farms with Network Design Algorithms. Master's thesis, Bergen University College, 2010.

[9] A. N. Letchford, J. Lysgaard, and R. W. Eglese. A Branch-and-Cut Algorithm for the Capacitated Open Vehicle Routing Problem. *Journal of the Operational Research Society*, 58:1642–1651, 2007.

[10] F. Li, B. Golden, and E. Wasil. The Open Vehicle Routing Problem: Algorithms, Large-scale Test Problems, and Computational Results. *Comput. Oper. Res.*, 34(10):2918–2930, 2007.

[11] P.-E. Réthoré, P. Fuglsang, G.C. Larsen, T. Buhl, T.J. Larsen, and H.A. Madsen. TopFarm: Multi-fidelity Optimization of Offshore Wind Farm. In *The 21st International Offshore (Ocean) and Polar Engineering Conference, ISOPE-2011, Maui, Hawaii, June*, pages 19–24, 2011.