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Investigation of different methods to generate Power Transmission Line routes

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ABSTRACT

In this study, we analyze and then evaluate four methods for siting more than one Power Transmission Line (PTL) simultaneously. Specifically, we look at (1) the least cost path (LCP) inside a macro-corridor, (2) the simultaneous definition of two routes (3) many routes inside a macro-corridor and (4) non-corridor routes generation. We apply the methods to a case study of siting two lines to deliver power for Northeastern Alberta and evaluated based on a set of metrics including overall impacts, computational complexity, and the spatial variability of the proposed alternatives. The results show that when the range of stakeholders' values and concerns are incorporated into the siting model, the conventional LCP between the source of electricity and the destination is not necessarily the best solution. Rather, our findings show that among the methods examined in this study, non-corridor routes generation method tends to find the lowest impact alternatives.

1. Introduction

There is an increasing worldwide need for new Power Transmission Lines (PTLs) as the demand for electricity grows. PTLs have a variety of impacts on the environment, ecosystem and society. Most of these impacts are spatial, as they depend on the location of the terrain where the PTLs are placed. 'Power Transmission Line siting' is the regulatory process for the identification of the corridor in the terrain where a PTL can be placed. Siting PTLs is usually a very long process because of the difficulty in coming to a universally agreed solution amongst all the stakeholders, which includes all parties potentially affected by the construction and operation of PTLs [1] such as property owners, municipalities and transmission facility owners.

Traditionally, models that are developed to support the siting decisions are spatial models that optimize the techno-economic parameters of transmission lines while determining the line corridor. However, this approach fails to address the concerns of a large number of stakeholders in particular, affected landowners. Thus, the decision-making process can lead to significant stakeholder oppositions and subsequent delays in the approval phase [2–4]. An attempt to integrate the economic and environmental criteria is presented where satellite images are used as the input map and different qualitative weights are applied to select the best route [5]. However, conflicting stakeholders' values are not incorporated in this siting study type.

Besides stakeholder satisfaction, reliability is also a factor that shapes the siting decision. Spatial reliability becomes important particularly when system operators identify a need to build two (or more) PTLs [6]. These routes are normally separated by a pre-specified minimum distance to ensure the reliability of the power system [7] thus that the potential reasons for the failure of one line is unlikely to impact the parallel line simultaneously.

The common practice in transmission line siting that most studies in this field focus on is the utilization of one least cost path (LCP), such as Dijkstra's algorithm [8], to find a route with minimum cost across a set of specified criteria [9–15]. A limited number of studies discuss specific algorithms for generating alternative routes. The K-shortest loopless path (KSP) method and its variants were some of the earliest attempts to solve the problem of alternative routes generation (see online bibliography [16]). KSP uses a brute-force method of systematically listing all possible routes between a given origin and destination, then ranking them in order of length. Although the KSP method guarantees all possible paths are found within a cost threshold, it is not practical as it generates a massive number of possible paths that are spatially similar and share most of the attribute values [17]. Paths with similar attribute values do not aid in the decision-making process since they do not convey the full range of options that are available to decision makers. The KSP runtime and memory requirements increase factorially with solution space. Hence it is limited in all practicality to trivially small networks [17]. Subsequent algorithms

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have been proposed to find more spatially dissimilar alternatives. For example, the Iterative Penalty Method (IPM) is used to solve shortest path problems sequentially [18]. In IPM, new paths are generated and then some nodes or edges within the network are penalized to discourage their use in subsequent iterations. Depending on the extent of penalization, a different number of route alternatives can be generated. Although the alternatives may share some nodes and edges, they are more spatially separated compared to the alternatives obtained by the KSP [18].

The Gateway Shortest Path (GSP) technique is also proposed to generate spatially dissimilar alternatives. GSP makes it possible to generate a large number of such routes approaching the lowest cost that are partially dissimilar from the least cost path. However, GSP can generate alternative paths that are located too close to one another because it focuses on the geographical separation of the candidate paths to the shortest path only, and not to the subsequent paths [18].

Routes generation inside macro-corridors is also discussed in the literature. Macro-corridors are large regional areas which are identified as suitable for locating a PTL. By defining macro-corridors at the beginning of the siting process, the scale of the problem and its complexity is reduced. There are different approaches to determine a macro-corridor. One of the most applied method is EPRI-GTC [19] that is implemented in many siting applications (e.g., Ref. [20]). In this study, a macro-corridor is identified by selecting all paths that fall in the first natural break of a histogram of path options and the final proposed route is the LCP determined by GIS tools inside that macro-corridor. This route, however, is dependent on the parameters setting of the histogram. This approach is also unable to site more than one PTL at the same time for a common purpose. Another method for macro-corridor generation is map up-scaling. This approach has been proposed mainly for IC design and communication networks but as yet has not been applied to PTL siting; however, in terms of graph theory basics, there is an analogy between this field and geographical routing.

Given the diversity of stakeholders' objectives, identifying one single 'optimal' is not always possible. The generation of near-optimal alternative routes that are spatially dissimilar can help stakeholders explore tradeoffs between attributes during the siting process. Furthermore, siting more than one PTL to deliver power from a source point to the destination(s) is another issue that is not discussed extensively in the literature. This issue is important because in some circumstances, it is legislatively required to build two redundant power lines with a minimum separation distance to maintain the reliability of the system in case of catastrophic failure of one of the lines.

To the best of our knowledge, there is just one study that proposes a graph theory algorithm to find two simultaneous power lines between terminus points [21]. There is a gap in the literature for the evaluation of available methods to solve the specific problem of siting multiple PTLs.

In this paper, we provide a systematic comparative study. We review four existing siting methods from a new perspective that is not discussed before in the relevant literature. The new perspective which is unique for the current study is to adapt methods for the problem of multiple lines siting while considering stakeholders' values into the siting decision and to identify the circumstances under which each method is applicable or impractical. We have selected these methods from the currently published studies in the field of siting linear infrastructure and adapted them to the problem of siting two PTLs, where the reliability requirement dictates the separation of two lines.

We categorize the methods into two general groups. The first group finds one pair of routes at a time. It includes the following two methods:

(1) LCP inside macro-corridor,
(2) Simultaneous definition of two routes.

The second group generates several pairs simultaneously and consists of the following two methods:

(3) Many routes inside macro-corridor,
(4) Non-corridor routes generation.

The main contribution of this paper is the identification of the advantages and the limitations of each method for siting more than a single PTLs when stakeholder inputs are systematically incorporated into siting models.

We apply these four methods to a case study that focuses on connecting the electricity from a potential hydropower plant in northern Alberta to electricity demand centers approximately 400 km south by two transmission lines. To study the performance of these methods, we evaluate the generated alternatives against a set of criteria including economic costs, environmental and social impacts. We aggregate the performance of each technique with regard to all criteria through a multi-criteria decision-making (MCDM) approach. Therefore, we score all alternatives and determine a subset of the preferred routes. We compare methods along different metrics such as computational complexity, an overall 'impact' score of the preferred alternatives and the spatial dissimilarity of the resulting routes and discuss the circumstances under which the application of each method is preferred over other available methods and therefore, this analysis provides insights for the siting decision process.

The remainder of the paper is organized as follows: in Section 2, each method to be evaluated is described. A case study is presented in Section 3 to test the method in a typical geographical region. Sensitivity analysis, conclusions, and further applications of the study are discussed in Sections 4 and 5, respectively.

2. Methods

The following section contains four subsections. Section 2.1—the structure and data input format that applies to all four methods. Section 2.2—a single option (LCP inside macro-corridor and simultaneous definition of two routes), Section 2.3—multiple alternative options (many routes inside macro-corridor and non-corridor routes generation) and Section 2.4—the comparison of the siting methods. We develop all methods for the case where more than one PTL with a minimum separation distance is going to be sited to satisfy the reliability requirement of the power system. We have presented the procedure of the methods in detail in Supporting information (SI) (Figs. S1–S4).

2.1. Siting model input

First, we define the study region where the PTLs are to be sited. We collect a land cover dataset of the study region; that is, polygons that represent different types of land such as forests, water bodies and agricultural land. We use ArcGIS 10.1® [22] to convert land cover polygons to the raster format. Raster format consists of a matrix of cells where each cell specifies a unit area of land with a specific dimension and value that represents the land type [23]. Then, we assign a relative value from 1 to 10 to the cells in the land cover raster based on the ease of PTL construction in the region to which the cell belongs. If the value of a cell is 1, it is the most convenient place to site a PTL (e.g., flattest, no physical barriers) and if the value is 10, it is the least. The raster at this stage does not include stakeholder values or concerns related to different line features. We use this raster to create the graph model of the case study:

$$\text{Directed graph network} \quad G=(N, E), \tag{1}$$

$$\text{Node set} \quad N = \{u_1, u_2, \ldots, u_n\}, \tag{2}$$

$$\text{Edge set} \quad E = \{(u_1, v_1), \ldots, (u_m, v_m)\} \tag{3}$$

On the graph, the nodes are the raster cells and the edges are the connection of two adjacent raster cells that can be selected as a part of PTL route. A route is a sequence of edges that connect the source node, u_s to the destination u_d.

$$\text{Graph route} \quad P=\{(u_s, v_s), \ldots, (u_d, v_d)\} \tag{4}$$

In a weighted graph, each edge holds a positive 'weight'; this weight can be defined as the average of the value of adjacent nodes [24]. For the