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An affine adjustable robust model for generation and transmission network planning ☆

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ABSTRACT

This work studies an electricity generation and transmission network planning problem where loads and cost parameters are uncertain. The problem is to first determine the generation and transmission capacities to install in the supply network. When the uncertainties are revealed, a flow plan is developed to minimize the total costs and to balance loads. A two-stage mixed-integer programming model is proposed to maximize the robustness of the plan in achieving a total cost budget target. The modeling approach in this study synthesizes recent developments in affine adjustable robust optimization technology and decision-making behavior under uncertainty. A novel solution approach is also proposed to achieve a safe and tractable approximation of the model. This involves the partitioning of the total cost budget target in order to transform the original problem into a small collection of mixed integer programming models that can be solved efficiently using standard mixed integer programming solvers. Numerical studies using a power generation network are performed, which demonstrate that the proposed robust planning model performs favorably compared to a stochastic programming model across different performance measures. The computational results strongly suggest the ability of the robust planning model to effectively mitigate the effect of uncertainties.

1. Introduction

Global consumption of electricity as of 2011 is 22 trillion KW h, more than 2.5 times the consumption in 1975, and is expected grow at a rate of 2.2 percent up to 2040 (www.eia.gov/forecasts/ieo/world.cfm). The International Energy Agency estimates that the world will need to spend $12 trillion over the next thirty years just to provide the necessary electricity infrastructure to accommodate growing demand. Furthermore, generation fuelled by worldwide burning of hydrocarbons continues to negatively impact the natural environment. This has resulted in various environmental regulations to reduce total greenhouse gases (GHG), for example through imposing emissions mitigation costs and renewable generation portfolio standards. In the face of these challenges, effective planning of generation and transmission expansion continues to be an issue of critical national and state importance.

In this work, we propose a mixed integer programming (MIP) model for the planning of generation and transmission expansion under uncertainty. Basically, this concerns the selection of new generation units, transmission lines and their respective capacities, with economic considerations including capital costs, operational and fuel costs to meet projected load growths. Given the long development lead times of electricity infrastructure, many important system parameters cannot be accurately known in advance. These can include for example uncertainty in load projections, volatility in fuel costs due to global market conditions, uncertainty in transmission costs due to revisions in cost-sharing policies, and the impact of future environmental mitigation standards on operational and emission costs. Generation and transmission expansion plans formulated without carefully accounting for these uncertainties can yield serious negative economic and social impacts in reality. This is an area of active research, and some related works of interest are reviewed in our literature study in Section 2.

In the model we propose, the generation and transmission expansion problem of concern is framed as a two-stage network planning problem. The first stage involves the determination of new generation units, transmission lines, and their respective capacities. These decisions are assumed to be made and implemented before the uncertainties are completely resolved. The second stage decisions involves formulating an economic and feasible load-flow plan when the uncertainties are realized. A *robust optimization* approach is adopted to model the effects of parametric uncertainties in the problem. A key advantage of the robust

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optimization approach is that relatively few assumptions are required to model the uncertain parameters, as compared to stochastic optimization approaches. We view this as particularly relevant to the problem under consideration, since it may be difficult to assign probabilities confidently to uncertain outcomes associated with many factors such as new environmental mitigation measures (e.g. carbon tax rates) that does not have rich historical data availability. Another advantage of the robust optimization approach is its computational tractability. That is, if the original deterministic problem is tractable, then the robust optimization approach often yields counterpart problems that are also computationally tractable, such as linear programming or second-order cone programming problems. Specifically in our case, the deterministic generation and transmission planning problem is a linear MIP, and the robust counterpart problem can also be formulated as a linear MIP of moderate size.

In many actual applications, uncertain parameters may be correlated with each other. In this work, we allow such data correlations to be captured using *affine uncertainty models*, also called factor models of uncertainty. Also, because two stage robust optimization problems are generally computationally intractable, the use of an affine adjustable decision rule [3] is adopted in this work to model the second-stage operational decisions. That is, we restrict the space of all second stage solutions to those that are approximated as affine functions in the uncertain parameters. Although such a restriction can produce sub-optimal second-stage decisions, the advantage is in recovering a computationally efficient optimization model. The use of affine decision rules is also well motivated in the robust optimization literature and is shown to demonstrate reasonably good performance in practice. Unfortunately, our consideration of uncertain operational cost parameters further complicate the application of this approach, and renders the model difficult to solve. A technical contribution in this paper is in proposing an efficient approach to achieve a safe and effective approximation to the problem.

Another important and interesting feature of our proposed model is that, instead of minimizing total relevant costs, we allow the decision maker to specify a cost budget target, and the objective is to find a solution that best achieves this target under uncertainty. In many real world engineering design projects, the objective is to achieve specified performance goals, rather than trying to 'optimize' a single criterion. Target achievement behavior of decision agents has long been emphasized in pioneering works such as Charnes and Cooper [7], who proposed the use of success probability optimization as a prescriptive model of target achievement under uncertainty. Our proposed robust planning model in this work is inspired by such an approach. However, we do not use success probability as the target achievement criterion. Instead, we base our approach on robust optimization modeling techniques, and our objective is to obtain solutions that can maximize the robustness of achieving the stated cost budget target. Unlike success probability, our proposed model can be easily computed using safe and tractable formulations. Finally, we show that our choice of maximizing robustness of the planning solution is consistent with decision theory from an axiomatic perspective. This is also a novel contribution in the paper. Our proposed approach can also be easily extended to models including multiple budget targets if required.

The outline of the rest of the paper is as follows. The next section presents a literature review and critique of the recent research work of relevance. Section 3 introduces the basic generation and transmission expansion problem of focus in this work. In Section 4, the robust model for planning under uncertainties is presented. As a consequence of the uncertainties associated with the operational cost parameters, the optimization model is computationally intractable in general. In Section 5, some simple but safe and tractable approximations are developed, so that the resulting robust counterpart model can be solved directly using standard mixed integer programming solvers. In Section 6, computational studies for a generation and transmission planning problem is presented. Our computational results show that the proposed robust model solution outperforms an alternative approach based on stochastic optimization on various performance measures such as expected costs, variance and probability of achieving budget target. Detailed model solutions are also studied. In particular, we demonstrate how the robust design solution is able to effectively mitigate load shortfalls and CO_2 emission levels through strategies of capacity buffering, network interconnectivity and diversity of generation technologies. Finally, we conclude our work in Section 7.

2. Literature review

There are many works in the area of generation planning using optimization based approaches. For instance, Linares and Romero [19] apply a goal programming approach to model and analyze electricity planning in Spain. Their model solves for the generation capacities that best achieve the multiple objectives of the problem, which include the minimization of generation cost, GHG emissions and radioactive waste. Asadamongkol and Eua-arporn [1] propose a multi-stage integer model for solving transmission expansion planning (TEP) problems. A Benders decomposition algorithm is initially used to find cutting planes to the TEP problem. This is then followed by decomposing the problem into investment and operation problems in order to achieve an optimal plan. Chaudry et al. [8] consider a multi-period optimization model of a natural gas powered electricity generation network, with the objective of minimizing the operational costs associated with the supply of natural gas, gas storage operation, electricity generation, and load shedding while meeting load requirements over a prescribed time horizon. Vazhayil and Balasubramaniam [29] considered the optimization of a power generation mix as a strategy for climate change mitigation in India. The authors developed a multi-objective optimization model considering cost reduction, emissions reduction and risk mitigation. A hybrid algorithm in the form of Intelligent Pareto-search Genetic Algorithm is used to solve the model.

The aforementioned papers do not consider planning under uncertainty. In practice many problems in energy planning are plagued with uncertainties with various complexities in terms of information quality. Stochastic optimization is a popular methodology used to handle planning under uncertainty in the published literature. Most stochastic optimization models seek to optimize the expected costs or profits of the problem of concern. Delgado and Claro [10] proposed a mean-risk mixed integer linear programming model for transmission network expansion planning. Their study illustrates how different network designs feature different trade-offs between mean cost minimization and risk mitigation, focusing on the impact of network structure, loss aversion, variability, and demand correlation. Nowak and Romisch [23] develop a multi-stage stochastic programming model for a hydrothermal generation system. The objective of the model is to minimize the cost of distributing power within the system under uncertain load requirements. It is solved using a prescribed algorithm that evaluates start-up and shut-down decisions in the system. Liu et al. [20] introduced an integrated dynamic optimization approach with an objective of maximizing economic returns to manage resources availability and environmental regulations. Their work expresses the uncertainties as intervals and probabilities, to which they applied an integrated interval parameter programming and chance-constrained programming approach. Li et al. [18] used a multi-stage interval stochastic programming model to decide on