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A multistage stochastic energy model with endogenous probabilities and a rolling horizon

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ABSTRACT

Federal, state and local government-funded energy conservation and renewable energy projects are implemented by requesting large capital budgets at the beginning of a program. The technical and financial performance of these projects are uncertain given anticipated energy savings, varying energy costs, and sub- and super-additivity of energy projects costs and energy savings. The level of uncertainty is directly proportional to the length of the model's planning horizon and are further exacerbated when these savings are used for investment in future projects. A rolling-horizon model that updates certain exogenous factors as well as optimal decision variable values for past times is presented. This model is run using illustrative cases showing its vast improvement in computational speed to solve, total stages required and total cost to implement all projects over a fixed-horizon, multistage model. Lastly, both sub- and superadditivity of the annual energy savings of the projects is considered making the problem more challenging but realistic.

1. Introduction

The federal government buildings are one of the largest energy consumers in the world. In 2014, 39% of all federal energy was consumed by federal facilities. Energy consumed in federal government facilities has generally been declining over the past four decades. However; the reduction stems from both the total square footage occupied by the federal government, which continues to fall from its peak in 1987, and from the energy consumed per square foot inside federal buildings, which has been declining since 1975 [23]. While significant reductions in building energy intensity have been made, many more are required, while tougher challenges exist in funding energy conservation and renewable projects. Facility energy intensity fell short of the 27% goals of Executive Order 13423 and Energy Independence and Security Act to reduce energy intensity (Btu/GSF) with only a 21% reduction [29]. The remaining conservation opportunities will require ingenuity to both fund and implement the projects. However, funding energy conservation continues to follow a multiple-year and risk-averse process.

There are many approaches to the implementation of an energy or renewable project but most comprehensive energy programs begin with an assessment of current consumption and energy conservation opportunities at the individual building level. The initial assessment is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Level 2 Energy Audit. The audit is an onsite assessment and comprehensive energy analysis of the building's energy-using components resulting in a list of proposed energy conservation measures (ECMs) which include the following attributes:

- the proposed system or component description
- an estimate of the investment required to implement the measure
- an estimate of annual savings
- an estimate of the annual cost savings in dollars
- a performance measure such as simple payback ratio or savings to investment ratio

A typical set of these measures are shown below in Table 1.

The energy auditors determine the appropriate regulatory requirements as part of their scope of work in the contract with the Agency. The energy auditors then conduct audits to recommend the projects necessary to save the required energy. Projects that do not meet specific savings-to-investment ratios are not considered.

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Table 1
Typical energy conservation projects attributes.

Project Description	Investment Cost ($)	Annual Energy Savings (KBTU)	Energy Rate ($/KBTU)	Annual Savings ($)	Estimated Useful Life (years)	Payback Ratio (years)
Heating project	250,000	2,375,000	0.011	26,125.00	30	9.57
Lighting project	50,000	625,000	0.015	9375.00	15	5.33

All reported projects must be completed. The Agency's approach to implementing these projects is ultimately risk-averse. The Agency requests a conservative budget from direct appropriated funding[2] in the first stage and seeks to fund the required energy conservation projects. A stage is a one-year time period in the current research. Agencies would greatly benefit from innovation and novel approaches to assist in project implementation, funding and timing.

The technical and financial performance of these projects are uncertain and often managed by a, "wait-and-see" approach. Here we present original approaches that request reasonable budgets and allow for recourse actions. The savings from implemented projects are used for investment in future projects. However, anticipated energy savings, varying energy costs, and interaction between energy projects affect the ability of these models to predict future savings. A rolling-horizon model that updates the optimization model's inputs and optimal decision variable values for past stages is presented. This model is run using illustrative cases showing its vast improvement over a fixed-horizon, multistage model. These improvements are:

- a reduction in the total number of stages required to implement all projects
- the total cost to implement all projects
- the computational speed to solve a model with many decision and auxiliary variables

The value of the current work is the novel application and combination of several concepts such as multistage stochastic programming and subadditivity and superadditivity of energy savings from energy conservation projects using McCormick Inequalities [22] at several stages to improve on the current industry practice as well as adopting endogenous uncertainty in order for the agency to minimize the total cost of implementing all the energy conservation projects that it is considering.

The remainder of this paper is presented as follows. Section 2, discusses the current landscape project selection, stochastic optimization and rolling horizon methodologies, as well as provides context and highlights novelty of the current research. Section 3 presents the model formulation and Section 4 applies the model to experimental yet practical examples. Sections 5 and 6 continue with discussion of the results and conclusions, respectively.

2. Literature and context

2.1. Connection to project Selection/Knapsack problem and stochastic programming

A novel way to meet U. S. reduction and renewable goals is by using existing savings to fund future projects while accounting for uncertainty in implementation yields and energy prices. This requires selecting energy projects in a method that allow agencies to account for and reduce uncertainty associated with long planning horizons. As such, the current approach has a resemblance to a multi-stage, stochastic knapsack or project selection problem. The current methodology leverages annual savings in later stages from projects previously implemented which is analogous to securities in Markowitz's portfolio selection work [21]. The current problem also incorporates constraints on the cost of selecting projects, whereas the cost of the securities were not specifically limited in that earlier work.

In Asadia et al. [3] the authors present a multi-objective optimization model to assist stakeholders in the definition of measures aimed at minimizing the energy use in the building in a cost effective manner while satisfying the occupants' needs and requirements. However, the model described incorporates many subjective attributes, which make the quantification of value difficult. A multi-criteria knapsack model was proposed to help designers to select the most feasible renovation actions in the conceptual phase of a renovation project [1]. The additive knapsack model presented in that study was based on linear programming. The current research and the problem is much more complex as the benefits of each selection vary with time. Specifically, the period in which a project is selected, has a large impact on the benefit (annual savings) and the certainty of the benefit. Gustafsson used a mixed-integer, linear programming (MILP) model to minimize the life-cycle cost of retrofits subject to minimum space heating requirements [19]. The author showed that a building's heating system could be described mathematically in the form of a MILP. The primary objective of the research here is energy savings with cost being a secondary consideration as well as a two-level optimization approach to model the ECM decision process more accurately. A two-level optimization approach is modeled in Champion and Gabriel [10]. However, in the current research, the budgets are funded by direct appropriation, which is best modeled by a single objective function. Cano et al. presented a fixed-horizon deterministic energy technology selection model with an objective function that minimizes the total cost of energy subsystems throughout a 16-year horizon [7]. The Cano et al. work considers the performance of the installed technology through the operational variables in that model. The deterministic model is extended to a stochastic approach [9].

The current research models retrofits for building system and components and does not include the purchase price for energy. The current research extends the Cano et al. model by leveraging short-term performance for funding of future projects and optimizing over shorter, rolling horizons. The above are just a small sample of some project selection papers that have relevance to the current work. For further details, see Models and Method for Project Management [17].

The current approach is based on a multistage stochastic program for project selection. This area has been well-studied with early developments in Dantzig [12], Beale [5], and Charnes and Cooper [11]. In terms of energy systems, in Cano et al. [8], a decision supports system to manage energy sub-systems in a more robust energy-efficient and cost-effective manner was presented. In this paper, a two-stage stochastic model is proposed, where some first-stage decisions regarding investments in new energy technologies have to be taken before uncertainties are resolved [9]. Later recourse (second-stage decisions) on how to use the installed technologies are taken once values for uncertain parameters become

[2] Financing energy projects through appropriations allows federal agencies to own their projects and immediately benefit from the cost savings. This type of financing should be an agency's first consideration in pursuit of its renewable energy goals given the hierarchy of action items in Executive Order 13693 [15].