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Decision Support

Interior analysis of the green product mix solution

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ABSTRACT

When modeling optimal product mix under emission restrictions produces a solution with unacceptable level of profit, analyst is moved to investigate the cause(s). Interior analysis (IA) is proposed for this purpose. With IA, analyst can investigate the impact of accommodating emission controls in step-by-step one-at-a-time manner and in doing so track how profit and other important features of product mix degrade and to which emission control enforcements its diminution may be attributed. In this way, analyst can assist manager in identifying implementation strategies. Although IA is presented within context of a linear programming formulation of the green product mix problem, its methodology may be applied to other modeling frameworks. Quantity dependent penalty rates and transformations of emissions to forms with or without economic value are included in the modeling and illustrations of IA.

1. Introduction

Let greening product mix refer to the manner in which the environmental impact (e.g., carbon footprint or volume of CO_2 emissions) of production is incorporated within the mathematical modeling of what, how, and how much to produce. It should reflect the organization's intention to (i) restrict or eliminate the impact quantities and (ii) account for their economic consequences. In the modeling, the greening may take form in a variety of ways. It may appear as restrictions on the volume of certain emissions and other by-products of production; restrictions that relate to energy consumption or a preferred mix of energy sources, e.g., coal-fired, hydro, nuclear, etc.; charges that reflect penalties associated with emission generation and disposal; costs associated with emission treatment; and a representation that reflects the organization's participation in the trading of unused amounts of a regulated emission allowance. The exchange is known as cap-and-trade and in some situations a trading forum exists, see Galbraith (2013), Jaehn and Letmathe (2010), and Letmathe and Balakrishnan (2005). Modeling green product mix may also include the transformation of the impact quantities to environmentally less harmful and possibly marketable commodities and products. The transformations may occur within the operations environment in which the mix products are produced and may compete for use of the resources therein.

Modeling product mix under emission restrictions and a single measure or objective of what is best is generally straightforward. However, the optimal product mix that accommodates all sought after emission controls may exclude flagship product(s); result in product volumes that may challenge maintenance of market share or be so disparate that it creates problems in moving product through the various fabrication processes; upset product/process fit; call for underutilization of expensive resources; or most importantly result in a prohibitive reduction in the optimizing objective. Clearly, the value of the objective under emission restrictions cannot be better than the value of the unrestricted product mix solution.

When the modeling produces a green product mix solution with prohibitive results, the following is proposed for assessing cause. Suppose information was available that would allow the analyst to identify the results of successive one-at-a-time accommodations of the emission restrictions within the green product mix model of interest. By stepping through the greening in this manner, the analyst can track and attribute cause and effect to the diminution in the objective (e.g., profitability) with each accommodation. At some point, a prohibitive reduction in the objective will emerge and the causative emission restriction identified. This is referred to as the tipping point. Assuming the restrictions do not uniformly impact the objective, a reasonable way to begin the investigation is the identification of the single least detrimental emission restriction to incorporate in the model, followed by the least detrimental

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pair that includes the least detrimental single emission restriction, and to proceed similarly until all emission restrictions are accounted for. The necessary information for proceeding in this manner is found among the solutions to all subproblems of the green product mix problem in which the emission restrictions are accommodated one at a time, in pairs, triples, etc. Each subproblem represents a scenario of specified inclusions and exclusions among the set of emission restrictions under study, a subset scenario. The generation and use of the subproblem scenarios constitute interior analysis (IA), the subject of this paper. In the literature of green product mix modeling, this method of investigation is not well developed.

The results of IA may be useful in a variety of ways. For example, emergence of the tipping point may move the decision maker to consider alternate implementation scenarios. The merit of scenarios without the offending emission restriction and its combination with restrictions that compound the loss in the objective may be considered in formulating a strategy of partial implementation. Although some emission controls would not be explicitly enforced in these scenarios, their proximity to desired targets may be acceptable. Or the identified emission restriction(s) may be voluntary not mandated and as such postponable and eliminated from current consideration. The identification of the tipping point may also help the analyst assess the magnitude of needed offsets to the loss in the objective due to imposition of the emission restrictions.

In other ways, examination of all subsets of emission controls using IA has analytical value. They may reveal features of the green solution set that would not otherwise be evident. For example, the subproblem results provide insight to the manner in which the product mix quantities vary with the emission restrictions. Enforcement of some emission controls individually or in combination with others may eliminate some products from the mix and drive others to their upper bounds. In other situations, the values of certain product mix quantities may be invariant in any scenario of emission control. They are robust with respect to the greening.

In this paper, IA is illustrated within the framework of a linear programming (LP) formulation of a green product mix problem. Although the LP form of a green product mix model is not the totality of representations, it is the form of many mix models discussed in the literature. Its form is easily understood and amenable to the editing that is required for streaming all possible scenarios of emission control. A procedure for streaming the scenarios and organizing the results for IA is presented in this article.

Without loss of generality, emissions will refer collectively to the gases, solid wastes, effluents, scrap, etc. that result from production and whose return to the environment in untreated state would be harmful, illegal, or perceived as poor citizenship. Transformed emissions include recycled materials, recovered compounds, treated effluents, composited by-products, and other forms.

The rest of the paper is organized in the following manner. Literature relating to greening, its place in product mix determination, and strategies for implementation are reviewed in the next section. The formal presentation of the methodology of IA appears in Section 3 and illustrated with examples in Section 4. The paper concludes with summary and remarks in Section 5.

2. Literature review

The following literature discussion is intended to provide context for the modeling framework in which IA is illustrated. The context is found in the literature of the product mix problem and its green form as well as the literature of the mitigation of greenhouse gas emissions and other by-products of production. Other contributions related to the subject of this paper are found in the literature of waste disposal and post-optimality analysis of the product mix solution.

2.1. Literature of the product mix problem

Early in its history, the product mix problem was formulated as an LP problem and applied in a wide variety of settings. Over time, formulation innovations emerged to address special features of the decision making environment. They included fuzzy features such as the decision maker's ability/inability to rationalize the tradeoffs in product mix decision making. Recent contributions to accommodate fuzzy modeling aspects included Bhattacharya and Vasant (2007), Bhattacharya, Vasant, Sarkar, and Mukherjee (2008), Hasuike and Ishii (2009), Kunsch, Springael, and Brans (2004), Kunsch and Springael (2008), and Tsai and Hung (2009). Susanto and Bhattacharya (2011) accommodated fuzzy features under multiple objectives. Bhattacharya, Sarkar, and Mukherjee (2006) utilized an analytical hierarchy process (AHP) in modeling product mix determination and Chaharsooghi and Jafari (2007) used simulated annealing. Other contributions included accommodation of activity-based costing (ABC) aspects and theory of constraints (TOC) approach to the determination of optimal product mix. For the latter, see Plenert (1993). Kee (1995) incorporated both. The integration was intended to capture the interaction between costs (direct and indirect) of production and resource capacity (utilization and expansion) in determining optimal mix. Kee and Schmidt (2000) presented a model in which ABC and TOC solutions were special cases. Malik and Sullivan (1995) also addressed ABC aspects in their modeling. Onwubolu (2001) combined tabu search and TOC and Onwubolu and Mutingi (2001a, 2001b) investigated use of genetic algorithms and TOC in modeling product mix determination.

2.2. Literature of green product mix determination

Contributions to the greening of product mix determination are found in a variety of sources and consist of mathematical models, modeling methodologies, and formulation innovations for the abatement of a variety of emissions that accompany the production of the mix products. The contributions of Kunsch et al. (2004), Kunsch and Springael (2008), Mirzaesmaeeli, Elkamel, Douglas, Croiset, and Gupta (2010), Mollersten, Yan, and Westermark (2003), and Tsai et al. (2012) addressed CO_2 reduction; Dvorak, Chlapek, Jecha, Puchyr, and Stehlik (2010), the mitigation of dioxins and NO_x emissions; and Lu, Huang, Liu, and He (2008), the abatement of greenhouse gas emissions (e.g. CO_2, methane) resulting from the treatment/disposal of solid waste. Jaehn and Letmathe (2010), Letmathe and Balakrishnan (2005), and Rong and Lahdelma (2007) formulated for modeling purposes the trading of unused emission allowances. Rong and Lahdelma (2007) also contributed a multi-period stochastic optimization model for the combined production of heat and power among multiple installations. Their model incorporated emission penalties and the trading of unused CO_2 emission allowances. Lu et al. (2008) addressed uncertainty among environmental parameters using interval-parameter programming methodology in their mixed integer programming model of solid waste disposal. Kunsch and Springael (2008) utilized fuzzy reasoning methodology to address parameter uncertainties in their modeling of electricity production for residential distribution. In the modeling, they included a carbon tax scheme based on the fossil fuel used to produce electricity. Mirzaesmaeeli et al. (2010) provided a deterministic multi-period mixed integer linear programming model for the determination of the optimal mix (sourcing) of electric