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An optimization methodology for identifying robust process integration investments under uncertainty

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ABSTRACT

Uncertainties in future energy prices and policies strongly affect decisions on investments in process integration measures in industry. In this paper, we present a five-step methodology for the identification of robust investment alternatives incorporating explicitly such uncertainties in the optimization model. Methods for optimization under uncertainty (or, stochastic programming) are thus combined with a deep understanding of process integration and process technology in order to achieve a framework for decision-making concerning the investment planning of process integration measures under uncertainty. The proposed methodology enables the optimization of investments in energy efficiency with respect to their net present value or an environmental objective. In particular, as a result of the optimization approach, complex investment alternatives, allowing for combinations of energy efficiency measures, can be analyzed. Uncertainties as well as time-dependent parameters, such as energy prices and policies, are modelled using a scenario-based approach, enabling the identification of robust investment solutions. The methodology is primarily an aid for decision-makers in industry, but it will also provide insight for policy-makers into how uncertainties regarding future price levels and policy instruments affect the decisions on investments in energy efficiency measures.

1. Introduction

1.1. Background

Several studies have shown that there are many opportunities for increasing the energy efficiency in industry by using process integration (IEA, 2007), but despite the fact that many of the suggested measures are shown to be profitable, few have actually been implemented. One of the main reasons seems to be that companies are not willing to take the risk associated with making such investment decisions because they lack good background information on their possible outcomes. The economically optimal choice of energy efficiency measures is dependent on, for example, future energy prices, policy instruments and the availability of new technologies, all of which are highly uncertain entities.

Although studies, for example in the pulp and paper industry (FRAM, 2005; KAM, 2003), show that many energy efficiency projects can become profitable, the conclusions from the studies are rarely clear on which measures to take, but rather give different advice for different scenarios. This is of course of little help when decisions have to be made before the outcome of uncertain parameters is known; picking the best decision for a high-price scenario could be the worst thing to do if ending up in the low-price scenario, and vice versa. A decision that is not the best one for any scenario could still be the best choice overall, because it acts as a hedge against future uncertainties, and thereby has a good enough profitability for every scenario. Such a solution, which is good for a variety of values of the uncertain parameters, is here said to be robust.

Uncertainties are especially important to consider in the optimization of strategic investments, when the decisions have to be made in the near future, but the investment will be affected by long-term variations and changes in energy market parameters.

In analyses of energy systems, one common way of dealing with uncertain parameters is to carry out a sensitivity analysis (Saltelli et al., 2004) to analyze the stability of the solution. Sensitivity analysis is a way to study how an optimal solution, that

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is, the optimal set of decisions, will change with changes in the input parameters. However, the optimal decisions to be made under uncertainty may never be revealed using this approach. Wallace (2000) posed the question: 'Is sensitivity analysis of any use?', and showed that it is far from being a good substitute for incorporating uncertainty directly into the optimization modelling. In short, sensitivity analysis will never reveal solutions for which flexibility has a cost, since flexibility is not an issue when each scenario is analyzed separately. When decisions have to be made before uncertainties are resolved, flexibility will, however, be of value, which might make it worth the extra cost. By formulating the optimization of investment decisions in a stochastic programming model, flexible solutions are considered, in addition to all of the solutions that would be revealed using sensitivity analysis.

1.2. Aims and scope

The aim of this work is to use existing mathematical modelling and methods for optimization under uncertainty (or, stochastic programming), and incorporate knowledge of process integration and process technology in order to achieve a better framework for decision-making regarding energy efficiency measures. The objective is to find the combination of investments that results in the highest net present value (NPV), which is expressed by the formula

$$\mathrm{NPV} = -C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where T is the economic lifetime (in years) of investments, r is the discount rate, C_0 is the initial investment, and C_t is the net cash flow (revenues minus costs) in year t. The net cash flow of the final year, C_T, is adjusted for the value remaining after the economic lifetime (the residual value). We have developed a multistage stochastic optimization model to improve the investment planning of energy efficiency measures under price and policy uncertainty. Here, instead of maximizing NPV for each scenario separately, the expected value of NPV over all scenarios is maximized. The initial investment is required to be the same for all scenarios since the first investment decision is taken before the outcome of the uncertain parameters is known. The objective function is hence to

$$\text{maximize } E[\mathrm{NPV}(x)] := -C_0(x_0) + \sum_{s \in S} p_s \sum_{t=1}^{T} \frac{C_t(x_0, x_s, \omega_s)}{(1+r)^t} \tag{2}$$

where E denotes expectation, S denotes the set of all scenarios s, p_s is the probability for scenario s to occur, $x = (x_0, x_s)$ where x_s is a vector of decision variables corresponding to scenario s and representing, e.g., investment decisions or operating plans, and x_0 is the vector of decision variables associated with the initial investment and which is independent of s. Further, the initial investment C_0 is a piecewise linear function of the decision variables, x_0, and the net cash flow, C_t, in year t is a function of the decisions, x, and the uncertainty parameters, ω_s, for scenario s. By optimizing the objective function given by Eq. (2), we expect to find solutions that improve the investment planning of process integration measures, both since this methodology may produce solutions that are not found in a traditional investment analysis, and since it makes it possible to find solutions that are robust (Svensson et al., 2008b).

When incorporating uncertainty into investment decision modelling, the resulting model naturally becomes a stochastic integer programming model (see the paragraph below). This is the framework that our methodology is based on. However, something should be said about the real options approach that explains the underlying economic assumptions for such a framework, which in this application can be regarded as a special case of stochastic programming. While traditional economic decision rules are based on either reversibility of investments or 'now-or-never' statements, such assumptions are in many cases not valid in real situations. Investments cannot usually be 'undone', but there is often a possibility of delaying them. When uncertainty is introduced, there might be a value of waiting if it leads to more relevant information being revealed and uncertainty thus being reduced. By investing immediately, this value would be lost. If there is a value of waiting, there is, in other words, an opportunity cost of investing. This opportunity cost is not accounted for by traditional investment rules (Dixit and Pindyck, 1994).

Multistage stochastic programming is one methodology for modelling the real options investment problem. The theory of stochastic linear programming is covered in, e.g., Birge and Louveaux (1997) and more recently in Ruszczyński and Shapiro (2003) and Kall and Mayer (2005). As for deterministic optimization, the introduction of integer or binary requirements on variable values makes the model considerably more time consuming to solve. The scenario tree modelling of the random variables further increases the size of the problem. However, the model will at least remain mixed-binary linear also with the introduction of uncertainties and will be possible to solve. Stochastic integer programming is described in, e.g., Louveaux and Schultz (2003) and Sen (2005).

In stochastic programming, it is acknowledged that decisions have to be made before uncertainties are resolved. This introduces at least two stages in the decision-making process. In this application, the first-stage decision is made on which initial investments should be carried out. As time goes on, the true values of the uncertain parameters such as energy prices are revealed. Then, in the second stage there is a possibility of reacting to the outcome of these resolved uncertainties. For our application, the second-stage decision concerns the operating plans for the different technologies in which investments were made in the first stage, in order to achieve maximum revenues. Second-stage decisions also involve decisions on further investments to be made at that stage, as a reaction to the outcome of the uncertain parameters. This kind of model with two types of decisions where the second one is a reaction to the first, as well as on the realization of the uncertain parameters, is termed a recourse model. The division of decisions into two stages is one of the main differences of stochastic programming compared to deterministic optimization and sensitivity analysis.

Since investment decisions in industry must be based on economic profitability, the default objective is an economic measure. However, not only have environmental issues attracted increasing concern, but future CO_2 emissions targets and policies are also strongly related to the uncertainties affecting these kinds of investments. Because of that, the model is adapted for analyzing CO_2 emissions. In this way, the trade-off between economic and environmental objectives can be studied.

Also for policy-makers promoting energy efficiency measures in industry, uncertainties are important to consider. Industries that invest in energy efficiency measures contribute to a reduction of CO_2 emissions. A high CO_2 emissions charge (in the form of a tax or tradable emission permit price) makes investments in CO_2 emissions reductions more favourable. On the other hand, if the future charge level is unknown, there is a high uncertainty regarding the expected future cash flows. Therefore, investments might not be realized although they should be favourable, because of the higher risk and increased difficulty of how to analyze the different investment opportunities.