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Target-oriented robust optimization of polygeneration systems under uncertainty

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ABSTRACT

Production of clean, low-carbon energy and by-products is possible through the use of highly integrated, efficient systems such as polygeneration plants. Mathematical programming methods have proven to be valuable for the optimal synthesis of such systems. However, in practice, numerical parameters used in optimization models may be subject to uncertainties. Examples include cost coefficients in volatile markets, and thermodynamic coefficients in new process technologies. In such cases, it is necessary for the uncertainties to be incorporated into the optimization procedure. This paper presents a target-oriented robust optimization (TORO) approach for the synthesis of polygeneration systems. The use of this methodology leads to the development of a mathematical model that maximizes robustness against uncertainty, subject to the achievement of system targets. Its properties allow us to preserve computational tractability and obtain solutions to realistic-sized problems. The methodology is demonstrated for the synthesis of polygeneration systems using TORO with an illustrative case study.

1. Introduction

Climate change due to carbon dioxide (CO_2) and other greenhouse gas emissions is widely considered to be a critical global environmental issue [1]. Energy generation is a major contributor to global CO_2 emission. Because of this, research in this area has focused on the development of strategies for improving the efficiency and environmental performance of power generating facilities. Process Integration (PI) techniques based on Pinch Analysis or Mathematical Programming play an important role in the optimal design of efficient industrial systems [2]. Flexible energy systems utilizing multiple inputs and generating multiple products offer significant potential to enhance sustainability [3]. For example, polygeneration systems have been introduced since these provide an opportunity for maximizing the utility of fuels by integrating process units for generating several types of products [4]. As a result, such systems have higher thermodynamic efficiency and lower emissions than equivalent stand-alone systems [5]. The concept of polygeneration dates back to the early 1980s, with the term itself having been first introduced in a NASA (National Aeronautics and Space Administration of the USA) technical report [6]. The term has been applied to related systems, including natural extensions of combined cooling, heating, and power (i.e., trigeneration) systems [7], as well as related systems producing electricity along with various fuel and chemical co-products [8]. The term “multi-energy system” (MES) was introduced more recently as a unifying concept that includes related concepts such as polygeneration systems, distributed multi-generation (DMG) systems, and so forth [9]. In general, polygeneration systems are comprised of commercially available components such as power sources (e.g., internal and external combustion engines, and fuel cells), heat sources (e.g., boilers and fired water heaters), refrigeration or cooling units (e.g., vapour compression or absorption chillers), as well as other process units, to generate secondary products. For example, membrane-based modules can be used to generate purified water, while from the definition adopted by Adams and Ghouse [8], additional process units may be similar to those found in process plants (e.g., chemical reactors and various separation processes). Such process units are, in effect, building blocks which can be configured into a polygeneration plant, whose principal

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innovation usually lies in the integration of these commercially available components. Polygeneration systems are particularly well suited for applications requiring secure, reliable supply of utilities (e.g., remote locations or sensitive facilities such as hospitals). In general, polygeneration systems offer advantages with respect to improved thermodynamic efficiency and reduced environmental footprint. However, it is interesting to note that investment risk caused by factors such as the volatility of fossil fuel prices remains a major obstacle to the widespread deployment of such systems [9]; furthermore, this was the case even in the first decade of the 21st Century, when fossil fuel prices reached historic peak levels [7].

The systematic design of polygeneration plants requires the simultaneous consideration of interdependent process units within a process network whose topology may or may not be initially well-defined [10]. Polygeneration systems are complex networks of processes integrated together to produce multiple simultaneous energy products such as power, heat, cooling, and others. To design complex structures such as the polygeneration system, various Process Systems Engineering (PSE) techniques have been proposed for the computer-aided synthesis of polygeneration plants [11]. Examples of different methods include Pinch Analysis [12], linear programming (LP) [13], mixed integer linear programming (MILP) [14], multi-criterion optimization [15], fuzzy optimization [16] and P-graphs [17]. Some techniques have focused on specific polygeneration configurations. For example, models for optimal synthesis of trigeneration plants using single-objective [18] and multiple-objective [19] formulations have been proposed. Likewise, optimal design of systems using diverse inputs and integrating provision for clean drinking water in remote rural sites has been addressed recently [20]. A fuzzy optimization model has been proposed recently for the synthesis of polygeneration systems with storage units to meet cyclic loads and uncertain demands [21]. In addition to design problems, optimization models [22] and P-graphs [23] have also been used for determining operational strategies under abnormal conditions. An algebraic approach to bottleneck identification in polygeneration plants has also been developed by Tan et al. [24]. Mancarella [9] reviews modeling techniques for MES, which includes polygeneration and related systems. In a recent paper, Ng and Hernandez [25] proposed a 3E framework for the comprehensive analysis of polygeneration systems considering energy, economic and environmental aspects.

In the case of considering the simultaneous design of a polygeneration system and evaluating its economic potential, techno-economic analysis proves to be an essential tool. Ng et al. [26] for example used it to assess different schemes of polygeneration plants with carbon capture and storage, Dael et al. [27] utilized it to evaluate a biomass energy conversion park while Khan et al. [28] focused on the assessment of the viability of a small-scale biogas based polygeneration system in Bangladesh. Insights gained from such analyses can further be enhanced by integrating the effect of uncertainties within the polygeneration system. There has been significant interest in optimal design under uncertainty in PSE. Different approaches exist, the most basic of which is sensitivity analysis [29]. A review by Sahinidis [30] surveyed various approaches used in PSE, such as fuzzy programming, stochastic programming, chance-constrained programming, to name a few. A robust optimization approach was proposed for polygeneration systems, based on the principle of separating design and operational decisions within the model [31]. Similar models have also been developed for related energy systems such as biorefineries [32] and biomass supply chains [33]. Andiappan et al. [34] recently developed a model for optimal design of trigeneration plants considering unit redundancy to address reliability aspects. These methods have primarily focused on uncertainties in various physical parameters, even though in practice, significant volatility occurs because of economic factors [35]. Consequently, a target-oriented robust optimization[1] (TORO) method is appropriate for addressing techno-economic risks arising from such uncertainties. TORO was proposed in 2014 by Ng and Sy [36] as an approach which determines a robust system design that can absorb uncertainties in key model parameters. The TORO approach has been used for such applications as transmission network planning [36] and workforce inventory [37], but to date has not been applied to PSE problems.

In this paper, a TORO model for the synthesis of polygeneration systems is proposed. This work thus represents the first application of TORO to any PSE problem in general, and to polygeneration system synthesis in particular. The approach is concerned in particular with managing the techno-economic risk associated with over-investing in capacity when demand for a product fails to materialize as anticipated, or when prices of inputs and outputs are subject to high levels of volatility. It is has been noted that such investment risks pose a significant barrier to the commercialization of polygeneration systems [7], which thus necessitates the development of systematic methods to address long-term uncertainties; such issues have been addressed through recently proposed approaches for such green technologies as heat exchanger networks [38] and solar thermal systems [39], for example. This work thus addresses an important research gap by applying TORO to address long-term investment risk in the synthesis of polygeneration systems. The rest of the paper is organized as follows. Section 2 provides the formal problem statement while Section 3 discusses the development of the optimization model utilizing the target-oriented robust optimization (TORO) methodology. Section 4 then presents a case study to demonstrate how the model works; the results are compared with those of deterministic optimization and stochastic programming methods to highlight the advantages of TORO. Finally, conclusions and recommendations for future work are provided.

2. Problem statement

The formal problem statement can be stated as follows:

- Given that a polygeneration system has m process units, utilizing fuel to generate n types of product output
- Given that the technological performance of each process unit is defined by a fixed set of proportions of input and output streams
- Given that there is a range for the required product demand for each product type n
- Given that there are risks brought by market fluctuations, a range for the unit cost of products (and raw materials) are indicated such that the upper (lower) and lower (upper) limits correspond to the most optimistic and most pessimistic scenarios respectively

The problem is to design the polygeneration system for maximizing its profit, while at the same time considering uncertainties from demand and prices of the product outputs and raw materials.

3. Model

The basic optimization model is given by Equations (1)–(5) wherein the overall objective function is to maximize the profit (Equation (1)). The profit is obtained from the total sales of the products less the costs incurred by the purchase of raw materials

[1] Note that the word "target" is used here in a different sense from the normal usage in Process Integration literature.

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