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Multi-objective optimization of industrial waste management in chemical sites coupled with heat integration issues

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ABSTRACT

This work presents a multi-period waste management multi-objective optimization, considering economic and environmental issues. The behavior of waste treatment units is included in the optimization problem as black-box models based on industrial practice. A multi-objective mathematical strategy based on the normalized constrained method is applied. An industrial based case study is analyzed. The proposed rigorous multi-objective optimization leads to reduced computation effort and better solutions in terms of solution quality, since waste stream scheduling has been included in decision-making. In addition, a sequential approach is followed to further estimate the minimum heat requirements for the different solutions obtained in the Pareto front using a MILP formulation of the heat exchange problem. Hot and cold sink requirements can be reduced by 80% and 99% respectively.

1. Introduction

Waste minimization, material recovery and utilities rationalization have been traditionally dealt as integral parts at the design stage of process plants (Barbosa-Povoa, 2007; Chakraborty & Linninger, 2002). However, once the production process is established, the management of the generated wastes and its coordination with the production processes and utilities systems have a crucial role in the optimal allocation of plant resources from economic and environmental perspectives (Melnyk, Sroufe, Montabon, & Hinds, 2001).

Waste liquid effluents originated from industrial activities contain contaminants and certain species, such as organic solvents, with material and energy recovery potential. Therefore, not only does industrial waste management stand as an end-of-pipe problem, but also as a potential origin of resources, which can result in significant benefits if material and energy integration strategies are used.

On the one hand, waste streams must meet discharge constraints imposed by environmental regulations before being disposed off in the environment. Hence, waste treatment plants comprise several technologies, such as incineration, wet-air oxidation, per-oxidation, catalytic incineration, or biological treatment (Chakraborty & Linninger, 2002), whose final objective is the removal of contaminants from the industrial effluents.

In practice, treatment allocation decisions are usually taken based on company-specific selection criteria, since the choice of the adequate option for an entire manufacturing site with hundreds of ever changing effluents becomes an overwhelming task (Chakraborty & Linninger, 2002). In the literature, this problem has been tackled as a design problem of wastewater treatment network, which is part of the water network problem involving mass exchange concepts. In this area, certain simplifications should be removed to reach more practical applications (Jezowski, 2008), for example rigorous process models, schedule optimization, heat integration or storage policies should be considered.

The waste management problem is usually classified as a subproblem of waste water treatment networks, which is part of water network problems (Jezowski, 2008). Optimization of industrial waste management has received scarce attention in the literature. However, an extensive work specifically related to industrial waste treatment management has been presented by Chakraborty and Linninger (Chakraborty & Linninger, 2002, 2003; Chakraborty, Colberg, & Linninger, 2003). The work combined informed search for systematical synthesis for structural alternatives with rigorous mathematical programming for selecting the optimal flowsheet and its operating parameters. They further extended their work to include uncertain parameters, and demonstrated how to develop and update long-term site wide waste reduction efforts and investment strategies under uncertainty. Recently, Jezowski (2008) identified an increasing number of papers on the topic of water networks, including wastewater treatment networks. The author stated that, in this area, research tends to embed batch wise operations, simultaneous heat and water integration, uncertain data and inter-plant integration. Yundt, Baetz, and Patry (1994)

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proposed heuristic and dispatching rules for the scheduling of hazardous-waste processing in integrated treatment facilities. Verdaguer, Clara, and Poch (2012) proposed a multi-agent paradigm for implementing a prioritization process based on the state of the agents in the system using an algorithm to maximize the overall volume and pollutant loads discharged from industrial activities. They stated that temporal overloads due to influent volumes and/or pollutants loads that exceed the system's capacity should be avoided to reach a high efficiency of the system. Thus, the interest in multi-objective optimization of industrial waste problems raised already in the 90s (Alidi, 1996) for the petrochemical and iron and steel making industry (Achillas, Moussiopoulos, Karagiannidis, Banias, & Perkoulidis, 2013). Cavin, Fischer, and Hungerbühler (2006) evaluated waste treatment options considering economic and environmental objectives under uncertainty. The authors proposed stream mixing policies and obtained the most-efficient treatment paths. Rerat, Papadokonstantakis, and Hungerbühler (2013) presented a multi-objective optimization for liquid waste management using industrially based LCA models and operating constraints. They introduced flexible mixing policy scenarios, which significantly reduced the operating cost and environmental impact.

From a methodological perspective, the benefits of including linear waste treatment models have been reported in the literature for the design problem of waste water networks. For example, Castro, Teles, and Novais (2009) presented an approach for the optimal design of distributed waste water treatment networks with multiple contaminants. It is a two-stage solution strategy in which the non linear programs are replaced by a succession of linear programs for each treatment unit, and the resulting network is the starting point for the general non linear problem tackled with a local optimization solver. Thus, Ponce-Ortega, Nápoles-Rivera, El-Halwagi, and Jiménez-Gutiérrez (2012) proposed a linear mathematical programming model for the global optimization of recycle and reuse of water networks design. They linearized the treatment unit costs using convex hull, and characterized the treatment units prior to the optimization tasks. They highlighted the benefits of such characterization, since the system could be formulated as a linear model. Likewise, the inclusion of linear based approximations to the actual process models could provide higher flexibility and better computational performance to the plant scheduling (Capón-García, Moreno-Benito, & Espuña, 2011).

On the other hand, sustainability has recently received increased attention in enterprises, since it involves positive social image which devote efforts to improve resource management and reduce energy consumption. In this area, energy integration aims at optimizing the energy use, namely heat power, fuel and utilities. Specifically, heat integration is an essential aspect of industrial processes since it is able to reduce the amount of hot and cold utilities consumed. Its consideration in early design stages can lead to more efficient designs; however, simultaneous consideration of production scheduling and heat recovery opportunities has also gained importance.

The methodologies for considering heat integration in batch scheduling can be broadly classified in simultaneous and sequential categories (Halim & Srinivasan, 2009). The former methods consider the scheduling and heat integration simultaneously, which can lead to global optima. However, limiting temperature is not usually considered for heat transfer, and the heat exchange superstructure network needs to be specified a priori. In contrast, sequential approaches split the problem into two distinct parts, which do not require simplifying assumptions such as one-to-one heat exchange or pre-installed heat exchanger units, at the cost of not guaranteeing global optimal of the integration problem.

In the batch process area, Barbosa-Povoa (2007) presents recent work related to integration of heat exchange issues with process design and retrofit. Thus, Fernández, Renedo, Pérez, Ortiz, and Mañana (2012) reviews the main works to achieve energy integration in batch processes and the main ways to implement heat recovery. In the past, energy savings in batch plants were neglected because it was believed that they were not as large as in continuous cases, which is not true for some batch operations. Therefore, conventional pinch analysis provides successful solutions for continuous processes, whereas alternative methods are required for non-continuous and variable rate processes since heat recovery is constrained by temperature, stream availability and time. As a result, mathematical algorithms and optimization strategies have been designed in order to allow energy integration of discontinuous processes.

Vaselenak, Grossmann, and Westerberg (1986) presented the first work to address heat integration in batch facilities. They tackled heat exchange between vessels over a given production schedule, combining a heuristic for matching hot and cold streams, with a mixed integer linear program for improving the heuristic results in those cases with restrictive target temperatures. Later, Corominas, Espuña, and Puigjaner (1994) presented a methodology for optimal heat exchange network design for multiproduct batch plants. It considered a campaign mode of plant operation and studied energy integration of each campaign using heuristic approaches. One of the first attempts to simultaneously consider heat integration and scheduling in batch plants was presented by Papageorgiou, Shah, and Pantelides (1994). In their work, new binary variables and additional heat balance constraints were defined in the state task network based formulation for considering direct and indirect heat transfer. The new model contained a high number of non linearities and non convexities, which highly increase the problem complexity. Lee and Reklaitis (1995b) presented a mathematical formulation to minimize the utility consumption by heat integration between batch tanks in the scheduling of a single-product batch plant under no intermediate storage policy. Heat exchange matches were considered between the streams which connect the batch units, and heat exchange times were assumed to be negligible. Thus, the authors considered that only one-to-one matches are allowed. Significant savings were reported in the utility cost by coupling heat integration with the rescheduling of operation times. Later, the authors extended the formulation to include non-negligible heat transfer times, matches from unit to unit, along with multiple heat exchange modes (Lee & Reklaitis, 1995a). Zhao, O'Neill, Roach, and Wood (1998) provided a systematic mathematical formulation based on cascade analysis for the general situation of rescheduling for optimal direct heat recovery in cyclically operated batch processes under no intermediate storage policy, leading to a mixed integer non linear (MINLP) formulation. They allowed multiple stream matching, but specific temperature intervals for heat exchange were created based on the supply and target temperatures of all streams in the process. Pinto, Novais, and Barbosa-Povoa (2003) proposed a mathematical framework for the design of multipurpose batch plants with direct heat integration, considering operational issues. Therefore, the optimal plant configuration was obtained, along with the processing operations, heat transfer policies and auxiliary equipment. Stream matching and heat requirements were based on the initial and final stream temperatures, and multiple stream assignment was disregarded. Later, a continuous-time mathematical formulation for direct heat integration of multipurpose batch plants was described by Majozi (2006). In this case, heat integration was based on one-to-one stream matching, and minimum temperature difference as well as intermediate temperatures for heat exchange are disregarded. The former work was further extended to consider heat storage in heat integrated multipurpose batch plants, and significant savings in utility consumption were reported (Majozi, 2009). The previous formulation was improved to include