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Optimization of energy and water use in multipurpose batch plants using an improved mathematical formulation

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HIGHLIGHTS

- A simultaneous optimization approach for energy and water.
- Time average model (TAM) and time slice model (TSM) are used for exact treatment of time.
- Multiple contaminants in a stream and temperature variation in processing task are considered.
- Case studies are presented to demonstrate that a better objective value is achieved.

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ABSTRACT

Presented in this contribution is a formulation that addresses optimization of both water and energy, while simultaneously optimizing the batch process schedule. The scheduling framework used in this study is based on the recent and efficient formulation. This formulation has been shown to result in a significant reduction of computational time, an improvement of the objective function and leads to fewer time points. The objective is to improve the profitability of the plant by minimizing wastewater generation and utility usage. From a case study it was found that through applying only water integration the cost is reduced by 11.6%, by applying only energy integration the cost is reduced by 29.1% and by applying both energy and water integration the cost is reduced by 34.6%. This indicates that optimizing water and energy integration in the same scheduling framework will reduce the operating cost and environmental impact significantly.

1. Introduction

In recent years, batch processes have been getting more attention due to their suitability for the production of small volume, high value added products. The flexibility of batch plants allows the production of different products within the same facility. Batch manufacturing is typically used in the pharmaceutical, polymer, food and specialty chemical industries as demands for such products are highly seasonal and are influenced by changing markets. A common feature of many batch plants is that they utilize fossil fuels as the energy source and use water for process equipment cleaning, due to inherent sharing of equipment by different tasks. Despite the advantage of batch plants being flexible, they also pose a challenging task to operate in a sustainable way. In the past, batch industries could tolerate high inefficiencies in energy and water consumption due to the high value of final products which outstrips the production costs. However, greater public awareness of the impact of industrial pollution, more stringent environmental regulations and escalating raw materials, energy, and waste treatment costs have now motivated energy and water saving measures for more sustainable operations (Halim and Srinivasan, 2011). Since scheduling, energy and wastewater minimization for multipurpose batch plants go hand in hand, published works in those areas are reviewed.

1.1. Scheduling of batch plants

Much research has been done on developing mathematical models to improve batch plant efficiency. The substantial advancement in modern computers allows the possibility of handling large and more complex problems by using optimization techniques. Excellent reviews of current scheduling techniques based on different time representations and associated challenges have been conducted (Méndez et al., 2006; Floudas and Lin, 2004; Shaik et al., 2006). In the reviews, with regard to time representation,

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the models are classified as slot based, event based and precedence based (sequence-based). In the slot based models, (Pinto and Grossmann, 1994; Lim and Karimi, 2003; Liu and Karimi, 2008) the time horizon is divided into "nonuniform unknown slots" and tasks start and finish in the same slot. On the other hand, slot models exist that use nonuniform unknown slots where tasks are allowed to continue to the next slots (Schilling and Pantelides, 1996; Karimi and McDonald, 1997; Reddy et al., 2004; Sundaramoorthy and Karimi, 2005; Erdirik-Dogan and Grossmann, 2008; Susarla et al., 2010). The event based models can also be categorized into those that use uniform unknown events, where the time associated with the events is common across all units, (Maravelias and Grossmann, 2003; Castro et al., 2004) and those that use unit specific events where the time associated with the events can be different across the units (Ierapetritou and Floudas, 1998; Majozi and Zhu, 2001; Janak and Floudas, 2008; Shaik et al., 2006; Shaik and Floudas, 2009; Li et al., 2010). The heterogeneous location of events across the units gives fewer event points as compared to both the global event based and slot based models. As a result, unit specific event based models are computationally superior. The sequence-based or precedence-based representation uses either direct precedence (Méndez and Cerdá, 2000; Hui and Gupta, 2000; Liu and Karimi, 2007) or indirect precedence sequencing of pairs of tasks in units (Méndez et al., 2000, 2001; Méndez and Cerdá, 2003; Ferrer-Nadal et al., 2008). The models do not require pre-postulation of events and slots. Seid and Majozi (2012) presented a mixed integer linear programming (MILP) formulation based on the state sequence network and unit specific time points, which can handle proper sequencing of tasks and fixed intermediate storage (FIS) policy. The model results in a reduction of event or time points required and as a result, gives better performance in terms of objective value and CPU time required when compared to previous literature models.

1.2. Energy integration in batch plants

Many heat integration techniques are applied to predefined schedules which are inherently suboptimal. Vaklieva-Bancheva et al. (1996) considered direct heat integration with the objective of minimizing total costs. The resulting overall formulation was an MILP problem, solved to global optimality, although only specific pairs of units were allowed to undergo heat integration. Uhlenbruck et al. (2000) improved OMNIUM, which is a tool developed for heat exchanger network synthesis by Hellwig and Thöne (1994). The improved OMNIUM tool increased the energy recovery by 20%. Bozan et al. (2001) developed a single step, interactive computer program (BatcHEN) used for the determination of the campaigns i.e. the set of products which can be produced simultaneously, the heat exchange areas of all possible heat exchangers in the campaigns and the heat exchanger network. This work addressed the limitation of the graph theory method for the determination of the campaign by Bancheva et al. (1996). Krummenacher and Favrat (2001) proposed a new systematic procedure, supported by graphics, which made it possible to determine the minimum number of heat storage units. Chew et al. (2005) applied cascade analysis proposed by Kemp and Macdonald (1987) to reduce the utility requirement for the production of oleic acid from palm olein using immobilized lipase. The result obtained showed savings of 71.4% and 62.5% for hot and cold utilities respectively. Pires et al. (2003) developed the BatchHeat software, whose aim was to highlight the energy inefficiencies in the process and thereby enabling the scope for possible heat recovery to be established through direct heat exchange or storage through implementation of cascade analysis.

Boer et al. (2006) evaluated the technical and economic feasibility of an industrial heat storage system for an existing production facility of organic surfactants. Fritzson and Berntsson (2006) applied process integration methods to investigate the potential to decrease the energy usage in the slaughtering and meat processing industry. The result obtained illustrates that 30% of the external heat demand and more than 10% of the shaftwork used can be saved. Morrison et al. (2007) developed a user friendly software package known as optimal batch integration (OBI). Chen and Ciou (2008) formulated a method to design an optimization of indirect energy storage systems for batch process. Their work aimed at simultaneously solving the problem of indirect heat exchange network synthesis and its associated thermal storage policy for recirculated hot/cold heat storage medium (HEN). Most of the previous works solved this sequentially. Foo et al. (2008) extended the minimum units targeting and network evolution techniques that were developed for batch mass exchange network (MEN) into batch HEN. They applied the technique for energy integration of oleic acid production from palm olein using immobilized lipase. Halim and Srinivasan (2009) discussed a sequential method using direct heat integration. A number of optimal schedules with minimum makespan were found, and heat integration analysis was performed on each. The schedule with minimum utility requirement was chosen as the best. Later, Halim and Srinivasan (2011) extended their technique to carry out water reuse network synthesis simultaneously. One key feature of this method is its ability to find the heat integration and water reuse solution without sacrificing the quality of the scheduling solution.

Atkins et al. (2010) applied indirect heat integration using heat storage for a milk powder plant in New Zealand. The traditional composite curves have been used to estimate the maximum heat recovery and to determine the optimal temperatures of the stratified tank. Tokos et al. (2010) applied a batch heat integration technique to a large beverage plant. The opportunities of heat integration between batch operations were analyzed by a mixed integer linear programming (MILP) model, which was slightly modified by considering specific industrial circumstances. Muster-Slawitsch et al. (2011) came up with the Green Brewery concept to demonstrate the potential for reducing thermal energy consumption in breweries. Three detailed case studies where investigated. The "Green Brewery" concept has shown a saving potential of over 5000 t/y fossil CO_2 emissions from thermal energy supply for the 3 breweries that were closely considered. Becker et al. (2012) applied time average energy integration approach to a real case study of a cheese factory with non-simultaneous process operations. Their work addressed appropriate heat pump integration. A cost saving of more than 40% was reported.

For a more optimal solution, scheduling and heat integration may be combined into an overall problem. Papageorgiou et al. (1994) embedded a heat integration model within the scheduling formulation of Kondili et al. (1993). Opportunities for both direct and indirect heat integration were considered as well as possible heat losses from a heat storage tank. The operating policy, in terms of heat integrated or standalone, was predefined for tasks. Adonyi et al. (2003) used the "S-Graph" scheduling approach and incorporated one to one direct heat integration. Barbosa-Póvoa et al. (2001) presented a mathematical formulation for the detailed design of multipurpose batch process facilities with heat integration. Pinto et al. (2003) extended the work of Barbosa-Póvoa et al. (2001) with the consideration of the economic savings in utility requirements, while considering both the cost of the auxiliary structures i.e. heat-exchanger through their transfer area and the design of the utility circuits and associated piping costs. Majozi (2006) presented a direct heat integration formulation based on the state sequence network of Majozi and Zhu (2001) which uses an unevenly discretized time horizon. The direct heat integration model developed by Majozi (2006) was extended to incorporate heat storage for more flexible schedules and utility savings in the later work by Majozi (2009). However, the storage size is a parameter in his formulation which is addressed later by Stamp