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Sustainable batch process retrofit design under uncertainty—An integrated methodology

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ABSTRACT

This work explores the problem of optimizing batch processes' retrofit design pursuing an increase of production efficiency and efficacy while accounting for the associated processes' sustainability, aspect that within the process industry is nowadays of increasing concern. Batch processes are often complex structures, where retrofitting is not always a straightforward procedure for the decision maker, requiring then supporting tools. Such tools are often characterized by having to deal with large scale optimization problems, where solutions are difficult to obtain. Moreover, the presence of uncertainty adds to the already complex problems an extra level of difficulty. Within this context, the present work proposes an integrated solution approach, uSB-Design, which aims to guide decision-makers in the definition of sustainable batch retrofit designs under uncertainty. The applicability of the proposed methodology is shown through a batch plant case study.

1. Introduction

The increasing importance of chemical plants' retrofit design is constantly observed, due to the need of costs rationalization and minimization of environmental impacts. This ought to be considered while maintaining plants efficiency and efficacy. Guinand (2001) defined retrofit design as: "The redesign of an operating chemical process to find new configuration and operating parameters that will adapt the plant to changing conditions to maintain its optimal performance." The retrofit problem in general and in batch process plants in particular, are complex problems (Barbosa-Póvoa, 2007) that require decision supporting tools enhanced with models and solution approaches that would be able to deal with the associated problems complexity. Based on this challenge several authors have been developing heuristics, meta-heuristics and optimization models attempting to systematize procedures that will help practitioners in their retrofit activities. However as identified by Barbosa-Póvoa (2007) and more recently in Moniz et al. (2015) new methodologies are still required, which should explore the integration of such approaches (heuristics and optimization methods) in order to solve the complex problems in a real time context. The study of such integrated approaches has recently gained the interest of some authors. Chibeles-Martins et al. (2010) presented a meta-heuristic approach to improve computation results of the design and scheduling of multipurpose batch plants using Simulated Annealing and compared the results with exact methods. Later on in 2013, Moniz et al. (2013) proposed a formulation based on the Resource Task Network for the optimal scheduling of multipurpose batch plants, where equipment redesign is considered simultaneously with scheduling decisions. The equipment redesign problem is defined by the implementation of modifications in the processing units so as to change their suitability to perform certain tasks. A solution approach to solve the resulted complex problem was devised. Seid and Majozi (2013) studied the design, synthesis, and scheduling of multipurpose batch plants. A based robust scheduling formulation was used as a platform for the integration of the design problem where the integrated approach explicitly considered the different locations of materials in the plant. Good computational times were obtained when compared with previous published formulations. In the same year Fumero et al. (2013) also addressed an integrated problem where a multi period MILP model for the design, planning and scheduling of multistage multiproduct batch plants was presented. Market fluctuations were considered in a multi period context where different production campaign in each period were operated. More recently, Patil et al. (2015), proposed a methodology that addresses simultaneously: design, scheduling, and control of multiproduct processes. This considers disturbances by the identification of their critical frequency, which is used to quantify the worst-case variability in the controlled variables via frequency response analysis. Demand

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Table 1
Models featuresí characterizations for batch process.

	Design	Scheduling	Planning	Multipurpose	Formulation	Uncertainty	Sustainability
Pinto et al. (2003)	X	X		X	Exact approach		X
Halim and Srinivasan (2006)					Meta-heuristics		X
Simon et al. (2008)	X				Meta-heuristics		
Carvalho et al. (2009)	X				Heuristics		X
Chen and Chang (2009)	X				Heuristics		X
Chibeles-Martins et al. (2010)	X	X		X	Meta-heuristics		
Nonyane and Majozi (2012)		X		X	Exact approach		X
Seid and Majozi (2013)	X	X		X	Exact approach		
Yue and You (2013)		X			Exact approach		X
Fumero et al. (2013)	X	X	X		Exact approach	X	
Adekola et al. (2013)		X			Exact approach		X
Seid and Majozi (2014)		X			Exact approach		X
Patil et al. (2015)	X	X			Methodology	X	
Li et al. (2015)		X	X		Meta-heuristics		X

uncertainty is addressed through scenarios where different probabilities of occurrence are considered.

When analyzing the above works no focus on sustainability aspects has been identified. However, such concerns are nowadays a reality. The sustainable development has raised its importance after the definition presented by WCED (1987) in the Brundtland Report: "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Afterwards, Elkington (1998) translated the sustainable development into three pillars: economic, environmental and social. These two works appears as seminal when defining sustainability and have been used widely by different authors as main references in the area. Today, sustainability is a top priority of any company and batch processes industries are not an exception (Carvalho et al., 2009). Some methodologies considering sustainability in batch process design have been presented in the literature, however the number of publications in this area is still limited. In (2003), Pinto et al. proposed a mixed integer linear formulation for design of multipurpose batch facilities, considering heat integration and economic utilities savings. Halim and Srinivasan (2006) presented an intelligent system for batch processes waste minimization, based on heuristic rules (BATCHENVOPExpert). Simon et al. (2008) proposed a decision support framework for batch processes' retrofit design based on a heuristic method. The framework identifies improvement opportunities in a batch plants through the analysis of the product market situation. Carvalho et al. (2009) proposed a methodology that screens the batch design alternatives using economic, environmental, and social aspects (e.g. safety indicators), in order to identify the batch process bottlenecks and propose new design alternatives. In the same year, Chen and Chang (2009) integrated task scheduling and heat recovery aspects into an unified framework for multi-purpose batch processes. A mixed-integer linear program (MILP) was developed, where the new formulation could be solved in a standalone mode or using an heat-integrated mode. In the heat-integrated mode, the processes was defined, while keeping the operation flexibility with slightly expanded model size. Nonyane and Majozi (2012), considered cyclic scheduling concepts applied to wastewater minimization and production schedule optimization in a multipurpose batch facility. The formulation is based on a continuous-time formulation. In 2013, Yue and You (2013) addressed a bi-objective approach of batch scheduling problems considering economic and environmental aspects. The profit rate was defined as economic objective, followed by the environmental objective defined per functional unit based on the life cycle assessment methodology. Each instance was formulated as a mixed-integer linear fractional program (MILFP), which is a special class of non-convex mixed-integer nonlinear programs. In order to globally optimize the MILFPs obtained, a tailored reformulation-linearization method and Dinkelbach's algorithm was used, followed by a multi-ojective approach, ε-constraint. Adekola et al. (2013) and Seid and Majozi (2014) proposed methodologies to address water and energy minimization, while schedule optimization was pursued. Adekola et al. (2013) explored opportunities for direct water and indirect water reuse while Seid and Majozi (2014) explored the presence of multiple contaminants in a stream as well as temperature variation. Recently, Li et al. (2015) proposed a hybrid optimization approach for sustainable process planning and scheduling, using meta-heuristcs. The honey-bee mating and annealing processes are simulated to optimize multi-objectives including energy consumption, make span and the balanced machine utilization.

Despite some work has been done on the design, plan and scheduling of batch processes while considering sustainability concerns, as summarized in Table 1 further work is still required.

From Table 1, it is possible to verify that it is still missing in the literature the association of uncertainty when dealing with the sustainable batch design. Additionally when considering the retrofit problem, which more often appears within existing plants, the identified need is still a reality. In this context, the present work presents a generic and systematic approach for the simultaneous design/retrofit and scheduling of multipurpose batch plants while considering sustainability aspects in an uncertain demand environment. Due to the complexity of the system under analysis, integrated approaches for the problem resolution are required. Thus an integrated methodology, the uSB-Design is developed in the present work. This consists on an iterative process that allows a continuous improvement of existing plants, based on a combination of heuristics and optimization steps that pursue performance improvement of the processes under study while accounting for mass and energy process alternatives and accounting for demand uncertainty.

The remaining sections of the paper are organized as follows. Section 2 presents a detailed description of uSB-Design approach and in Section 3 the uSB-Design is applied to a case-study and the obtained results are discussed. Finally, conclusions are drawn in Section 4.

2. Uncertainty sustainable batch retrofit (uSB-Design)

A methodology for sustainable batch retrofit design under uncertainty is proposed, the uSB-Design. This methodology analysis a batch design plant operation and identifies tasks, units or operating conditions that represent processes bottlenecks, based on which retrofit design alternatives are proposed that will eliminate the bottlenecks and/or improve the process performance. A bottleneck is defined as any path, task, unit or operation that is limiting the efficiency of the process and therefore that should be reduced or eliminated. For instance, a batch process might present