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Integrated condition-based planning of production and utility systems under uncertainty

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ABSTRACT

A general rolling horizon optimization framework for the integrated condition-based operational and maintenance planning of production and utility systems in process industries is presented. In brief, the proposed optimization framework considers for the production and utility units: (i) improved unit performance degradation and recovery models that depend on both the cumulative time of operation and the unit operating levels deviation of units; (ii) modified operating capacities under online cleaning periods; (iii) different types of cleaning tasks (flexible time-window and online or offline condition-based); (iv) alternative options for offline cleaning tasks; (v) limited availability of cleaning resources; (vi) the initial state of the overall system at the beginning of each planning horizon; and (vii) terminal constraints for the rolling horizon problem. Total cost constitutes the objective function of the resulting problem and includes unit operating costs, cleaning costs, energy consumption costs and resource purchases costs. The case studies solved show that when compared to solutions obtained by sequential approaches the proposed integrated approach provides significantly better solutions in terms of total costs (reduction from 5% to 32%), and especially in cost terms related to utility units operation, energy consumption, cleaning and startup/shutdown operations. Unnecessary cleanings and purchases of resources can be avoided by the proposed integrated approach. Overall, the significant reduction in total costs is a direct result of the enhanced energy efficiency of the overall system through the efficient generation and use of energy, the improved utilization of energy and material resources resulting in a more sustainable and cleaner production practices.

1. Introduction

One of the main goals of any process industry is to generate maximum revenues at low costs by maintaining high production levels in order to satisfy the demand for products. A means for achieving this is by following a plant-wide approach through the integrated management of operational and maintenance tasks in the overall process system (Zulkafli and Kopanos, 2016).

Major industrial facilities consist of interconnected production and utility systems. Fig. 1 displays a representative layout of production and utility systems for a process industry. Under this plant layout, the production system produces desired products from raw materials that may undergo several production processes, such as reactions or separations. These main production processes require large amounts of different utilities, such as power, steam, compressed air, industrial gases or water. Especially, energy intensive process industries have an onsite utility system that generate the major utilities required by the main production system. Combined heat and power units, gas or steam turbines, compressors, and boilers are examples of onsite utility systems. The raw materials of the utility system can be any type of fuel or other resource, such as atmospheric air or water. These materials undergo a conversion process in utility units to generate the desired utilities. Depending on the type of utility, chemical or physical conversion could take place in a utility unit (e.g., combustion or compression). Then, the generated utilities are supplied to the production system for its own operation and the production of intermediate or final products. Excessive amounts of utilities can be stored in buffer tanks (e.g., hot water), be recycled (e.g., steam), or in some cases be released to the environment (e.g., exhaust heat). Some utilities may be acquired from external sources under an associated cost, if the onsite utility system cannot meet the needs of the production

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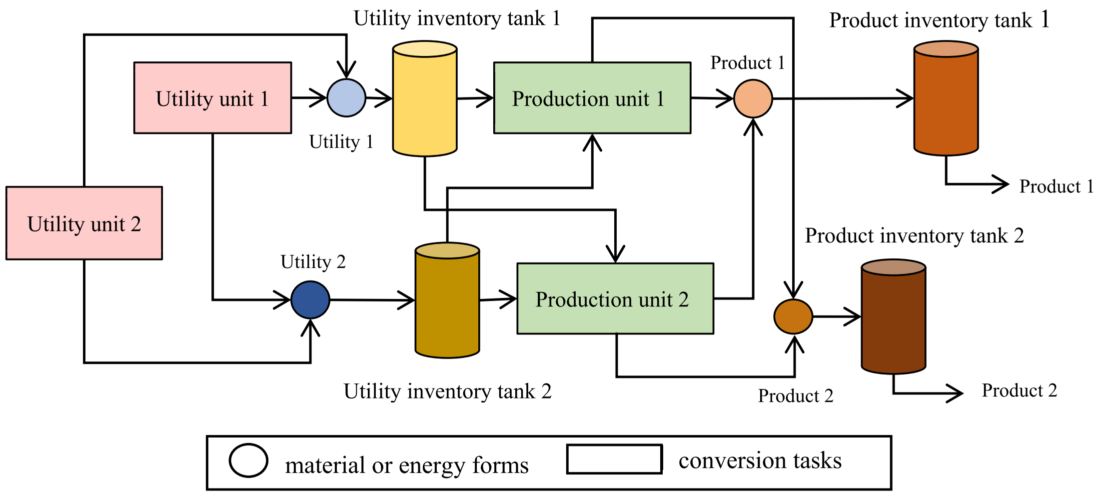

Fig. 1. Representative layout for the interaction of production and utility systems.

system (e.g., electricity from the power grid). Production and utility units may operate in parallel or in series depending on the overall process of their corresponding production or utility system. Final products or utilities can be stored in dedicated inventory tanks or directly satisfy the demand for products or the utility requirements of the production system, respectively.

In addition to the above, modern process plants consist of complex operating equipment that require maintenance to perform its required function in a timely manner to avoid equipment damage and inefficient use. Effective maintenance policies can sustain the operational level, reduce operating costs, and restrain the equipment and the overall system from entering hazardous states. The cleaning of production or utility equipment that are subject to performance degradation is one of the major maintenance actions in process industries. The purpose of this cleaning is to recover the performance (efficiency) of the corresponding equipment and decrease energy consumption over its operation. Thus, it is essential to consider condition-based maintenance policies for the equipment of a process plant to increase its overall energy efficiency, operability and stability (Xenos et al., 2016). To do this, performance degradation and recovery models need to be derived for each equipment and alternative maintenance policies need to be considered (e.g., online or offline cleaning).

Nowadays, process industries typically follow a sequential approach for the optimization of the operational plan of their production and utility systems. In this sequential approach, the planning of the production system is performed first by considering just upper bounds on the availability of utilities per time period. Once the production plan is derived, the utility needs of each production unit are known. This information is then used for obtaining the operational plan of the utility system. The main drawback of this approach is that it provides suboptimal solutions (with respect to energy efficiency and costs) since the two interconnected systems are not optimized simultaneously. Importantly, this traditional approach often faces the risk of providing generation targets for utilities that cannot be met by the utility system (infeasible solutions), and in that case either purchases of utilities would take place or a re-planning of the production may be needed (Zulkafli and Kopanos, 2016). Additionally, maintenance of production or utility units are typically predefined or follow a very conservative plan and not optimized by considering the actual operational plan of the overall process system.

In fact, most of the previous studies found in the literature have addressed individually the operational planning problem of production systems or the operational planning of utility systems. There are many works that addressed only the operational planning problem of production systems. For example, Shrouf et al. (2014) studied the production scheduling of a single machine to minimize energy consumption cost. Modarres and Izadpanahi (2016) presented a production planning model for a manufacturing plant considering energy planning, demand and production capacity. Ardjmand et al. (2016) proposed a multi-product production planning model for production plants under demand uncertainty. Zhou et al. (2017) developed production scheduling models for the textile industry. Other works focused only on the operational planning of utility systems. For example, Jin et al. (2015) developed a mixed integer programming model for the planning of power generation plants. Kopanos et al. (2015) presented an optimization framework for the operational and maintenance planning of compressors network in industrial air separation plants. Zhen et al. (2016) proposed a stochastic modelling approach for the planning of electric power systems. Chaturvedi et al. (2016) produced optimum water network schedule for multiple water resources. Abdul Aziz et al. (2017) studied the operational planning considering the integration of heat, cogeneration and power in industrial sites by using pinch analysis to reduce carbon emissions.

Also, some other works studied the maintenance planning (e.g., cleaning or repairing) of either production or utility systems. Some representative works on the maintenance planning for production systems are presented below. Nguyen and Bagajewicz (2010) developed preventive maintenance planning models for chemical process plants. Huang and Yu (2016) studied the maintenance planning problem with the objectives to reduce energy consumption and minimize makespan. Tayyab and Sarkar (2016) presented optimal batch size planning for manufacturing process to minimize total costs. Other works focused on the maintenance planning for utility systems. For instance, Cheung and Hui (2004) developed maintenance planning for industrial heat and power plant. Sanaye and Niroomand (2007) presented cleaning scheduling approaches for heat exchanger networks. Li and Nilkitsaranont (2009) studied the condition-based maintenance scheduling of gas turbine operations. Castro et al. (2014) addressed the optimal maintenance planning of a gas engine power plant.

In general, the operational or maintenance planning for utility or production systems have been studied separately in the