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Long-term turnaround planning for integrated chemical sites

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Dedicated to Ignacio Grossmann, an extraordinary teacher, mentor, collaborator, and colleague.

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ABSTRACT

An integrated chemical site involves a complex network of chemical plants. Typically, these plants interact closely, are dependent on each other for raw materials and demand for their products, and have the provision of intermediate storage tanks to help manage inventory at strategic points in the network. Disruptions in the operation of these plants can drastically affect flow of material in the site network. As a result, the choice of sequence and timing of planned periodic turnarounds, which are major disruptions, is important in order to minimize effects on profits and production. We investigate a discrete-time mixed-integer linear programming (MILP) model to perform turnaround optimization. The objective is to recommend potential schedules in order to minimize losses while satisfying network, resource, turnaround, demand, financial and other practical constraints. We propose general formulations to tackle this problem and study an industrial-size site network under various scenarios over a long-term horizon.

1. Introduction

A large-scale integrated chemical site constitutes a number of individual production units that are either connected to each other directly or through buffer storage capacities. These production units supply raw material to other units and produce final products that are ready to be shipped to end users. The tight integration of this network of plants provides synergistic opportunities for sharing raw materials, products, process and business information, domain knowledge, energy, utilities, manpower, safety infrastructure, and transportation. In addition, integrated sites may also benefit from holistic, long-term maintenance turnaround planning, which is the focus of this work.

Plant turnarounds are periodic, necessary disruptions in material flow through chemical production sites that not only incur enormous costs and consume resources, but also result in lost sales. As a result, turnarounds significantly affect demand and supply of materials within a chemical site network and are tightly coupled to production planning, resource planning and inventory management decisions. The purpose of this work is to present a modeling approach to optimize a turnaround schedule, while accounting for these practical considerations and constraints. We demonstrate the effectiveness of the model by applying it to a representative industrial-size chemical site network, and analyzing optimized schedules. Of particular interest is that the resulting schedules often lend themselves to the rational justification of the sequences and alignment of tasks, based on basic network structure and economic arguments. This gives further insight into the behavior of the network, a feature that will appeal to practitioners in the area.

Optimal turnaround scheduling of integrated chemical sites is a challenging combinatorial problem due to the following factors:

- *Operational constraints*: Due to complex flow relationships between production units, a turnaround performed on one of the units can result in blocking of upstream operations or starving of downstream operations. Typically these relationships require involved analysis because of the availability of buffer storage capacities, as well as priority rules for allocation of raw material under limited supply.

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- *Timing of turnarounds*: Each production unit in an integrated site has its own turnaround frequency and duration. In addition, depending upon the location of the site, turnarounds cannot be carried out during certain time periods in a year to ensure safety of the workforce. For example, for a site located in Northern Canada, it might not be appropriate to carry out the turnaround in winter months due to extreme weather conditions.
- *Resource constraints*: Turnarounds for a production envelope (a subset of plants that interact, are concerned with the same family of products, and are typically aligned with a specific business) within a site can require a large workforce of a few hundred personnel with different skill sets (such as welders, assembly workers, supervisors). Management and allocation of maintenance personnel in a site requires efficient planning and coordination. For instance, the sporadic requirement of a large workforce for a short interval can be difficult, as it is typical for such workers to be hired on contract. It may be difficult to ensure their hire if there are turnarounds being carried out by competitors, if the site is in a remote location, or if the logistics associated with a large workforce descending upon a site is cause for safety concerns.
- *Financial impact*: Turnarounds can have a significant impact on the revenue of the company. For a large integrated site, these turnarounds can lead to significant reduction in production rates and thus a reduction in short-term revenues. In order to reduce the impact on financial results, the turnarounds must be appropriately scattered over the planning horizon.

This work contributes to existing literature by (1) developing mixed-integer programming (MILP) formulations for long-term maintenance planning of integrated sites with continuous chemical plants; (2) incorporating financial performance, timing constraints, and manpower availability—considerations that require looking at a time and size scale not studied previously; and (3) demonstrating the real-world applicability of potential schedules that have been optimized under various scenarios.

Central to our approach is the mixed-integer linear programming model that we have developed for long-term maintenance planning. Ignacio Grossmann, the honoree of this special issue, has been largely responsible for introducing, developing and demonstrating the benefits of integer programming in chemical engineering via numerous publications that have addressed algorithms for MINLP (e.g. Duran and Grossmann, 1986; Viswanathan and Grossmann, 1990), disjunctive and logic-based programming (e.g. Raman and Grossmann, 1994; Lee and Grossmann, 2000), process synthesis (e.g. Papoulias and Grossmann, 1983; Yee et al., 1990; Karuppiah and Grossmann, 2008), project and supply chain planning (e.g. Sahinidis et al., 1989; Perea-Lopez et al., 2003; Guillén-Gosálbez and Grossmann, 2009), and process scheduling (e.g. Sahinidis and Grossmann, 1991; Pinto and Grossmann, 1995, 1998; Jain and Grossmann, 1998; Maravelias and Grossmann, 2003).

The remainder of Section 1 provides a brief background on turnaround scheduling and a literature review on maintenance planning in various industries, including the process industry. Section 2 provides an example network structure, the associated unit information required for optimization, and uses a small network example to motivate the potential for optimization. Section 3 outlines the solution approach, and provides details of the MILP model. Section 4 provides results, and a detailed analysis of them along with financial and sensitivity studies, and alternative formulations and results for other scenarios. Finally, Section 5 summarizes the work and discusses possible extensions and directions for future study.

1.1. Definition, concepts, and significance of maintenance scheduling

Maintenance can be defined as all actions appropriate for retaining an item/part/equipment in, or restoring it to a given condition (Dhillon, 2002). A maintenance turnaround is the periodic shutdown of chemical plants for overhaul. These turnarounds may be required to (1) prevent unplanned shutdowns due to equipment failures or wear and tear (e.g. in the case of pumps and compressors), (2) replace aging parts and instrumentation, (3) perform cleaning of pipes and equipment, (4) replace catalysts, and (5) perform welding or other structural reinforcement tasks.

Approaches to maintenance scheduling vary widely and depend on (1) whether the maintenance is preventive, corrective, or opportunistic; (2) what the sources of uncertainty in the operations are; (3) whether operations are multipurpose batch processes or continuous plants; and (4) whether maintenance planning is short-term or long-term.

The American National Standards Institute (2014) defines maintenance as *the planned maintenance of plant infrastructure and equipment with the goal of improving equipment life by preventing excess depreciation and impairment*. On the other hand, planned corrective maintenance is the maintenance carried out after a failure has occurred and intended to restore the item to a state in which it can perform its required function. Opportunistic maintenance is the exploitation of failure events to plan other maintenance activities in conjunction, and the altering of future maintenance schedules based on this.

Long-term maintenance planning uses information such as equipment reliability, usage, and maintenance histories and manufacturers recommendations to determine the approximate moments or frequencies of preventive maintenance. The solution to this problem may result in a list of equipment items that are due to be maintained over the next short-term scheduling period.

The primary task in short-term maintenance scheduling is to develop a scheme with detailed timing of maintenance activities that allots resources (maintenance crews, workers, and equipment) to tasks (machines or units) and satisfying certain constraints (such as crew availability, network constraints, or shift constraints), while not only maintaining regular production or operation to satisfy customer demand, but to do it in an optimal fashion so as to minimize losses, down-times, customer dissatisfaction, or some other metric. On many occasions, if a production schedule is also required, it is done side-by-side (either simultaneously or in a sequential-iterative manner) with the maintenance scheduling.

According to Christer and Whitelaw (1983), annual expenditure on maintenance by a medium-sized company at the time exceeded GBP 1 million. Tan and Kramer (1997) provide extensive references for costs from production losses due to equipment down-time. They estimate that lost production costs in a chemical plant may range from $500 to $100,000 per hour; and that refineries experience about 10 days of down-time every year, with losses of up to $30,000 per hour. Grievink et al. (1993) estimate that about 50% of operating cost variability comes from maintenance. Large chemical companies budget annually for spending on the order of hundreds of millions of dollars on maintenance, just for parts and manpower and not including the value of lost sales. According to a more recent estimate by Industrial Info Resources (2014), a global marketing intelligence agency, major ethylene plants commonly schedule turnarounds once every few years, where the average duration is 25 days at an average cost of $15 MM or more (Global Ethylene Database, 2014). Fig. 1 shows that in 2008, 408 turnarounds in active projects in the chemical process industry in North America were valued at a cumulative amount of around $1,034 MM (North American Chemical Processing Industry Maintenance Turnarounds, 2008). Thus, maintenance optimization