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Medium-term maintenance turnaround planning under uncertainty for integrated chemical sites

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ABSTRACT

Plant maintenance poses extended disruptions to production. Maintenance effects are amplified when the plant is part of an integrated chemical site, as production levels of adjacent plants in the site are also significantly influenced. A challenge in dealing with turnarounds is the difficulty in predicting their duration, due to discovery work and delays. This uncertainty in duration affects two major planning decisions: production levels and maintenance manpower allocation. The latter must be decided several months before the turnarounds occur. We address the scheduling of a set of plant turnarounds over a medium-term of several months using integer programming formulations. Due to the nature of uncertainty, production decisions are treated through stochastic programming ideas, while the manpower aspect is handled through a robust optimization framework. We propose combined robust optimization and stochastic programming formulations to address the problem and demonstrate, through an industrial case study, the potential for significant savings.

1. Introduction

The reliability and structural integrity of process equipment deteriorates over time due to wear and tear. Maintenance turnarounds on chemical plants are vital for maintaining plant productivity and safety, while securing long-term plant performance and providing opportunities for system upgrades. However, they pose sporadic, temporary disruptions in production, necessitating careful demand considerations, inventory planning, and man management. This effect is exacerbated in integrated sites, where neighboring plants in the site network may also be affected.

Turnarounds represent a significant expense for companies, both in terms of loss in revenue as well as direct turnaround costs (manpower, equipment, and parts). Annual budgets of large chemical companies run in the hundreds of millions of dollars, adding to the importance of this problem. We expound on the importance of turnaround planning in earlier work (Amaran et al., 2015).

From a turnaround planning perspective, there is uncertainty in what tasks need to happen, in the delivery of materials, as well as in weather conditions. As a result, a major portion of the uncertainty lies in the duration of the turnaround. To quote Lenahan (1999), "*there are only two types of work on a turnaround, routine and unexpected. If the routine is under control there is time to deal with the unexpected but if the routine becomes unexpected the unexpected may become catastrophic.*"

As observed by Lenahan (1999) and Narayan (2004), a large portion of the turnaround work scope is hidden due to inaccessibility to plant equipment. When plant units are taken off-line for maintenance, a more accurate assessment of the state of the equipment is performed, which is termed 'discovery work.' Discovery work may reveal that certain pieces of equipment are damaged worse than expected, resulting in an increase in maintenance duration that could even be on the order of maintenance duration itself. Uncertainty in the delivery of materials also leads to a delay in the duration of a turnaround. Other factors that can contribute to such delays are weather conditions and skill levels and efficiencies of manpower.

Uncertainty in turnaround duration affects both manpower availability as well as financial performance. In terms of manpower, maintenance personnel are typically hired on contract several months in advance, and the duration for which they are required to be made available is an important issue. When the duration is uncertain, we have the challenge of turnaround coordination while allocating limited manpower resources between the turnarounds with ensured availability. From a financial perspective, every additional day of plant down-time can result in loss of millions of dollars

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in revenue due to lost sales (Tan and Kramer, 1997). Delays also result in higher costs due to site integration losses, additional manpower and discovery costs. This makes it critical to deploy robust inventory management strategies to balance operation in such systems.

In this study, we investigate the turnaround planning problem under uncertainty over a medium-term time horizon that allows for the prior negotiation for manpower and for building downstream inventory in anticipation of a turnaround. Specifically, we develop two approaches to consider the uncertainty in turnaround duration that combine stochastic programming and robust optimization. The objective is to develop a robust turnaround plan that maximizes the overall profit of the entire chemical site while considering the raw material, inventory, and maintenance costs; demands and manpower limits; and network flows and turnaround duration estimates. While modeling this problem, we demonstrate how uncertainty in a parameter appearing as an index of a formulation may be transformed into left-hand side parameter uncertainty—this technique may be relevant for other problems as well.

The paper is organized as follows: In Section 2, we briefly introduce prior work in maintenance scheduling and process scheduling under uncertainty. We follow this with a discussion of the problem in question and the key decisions involved, and an outline of the solution approach we take. In Section 3, the strategies and mathematical models we use to handle the uncertainty in turnaround duration are described in detail. In Section 4, we present results on an industrial case study, where we contrast and compare different approaches, from both methodological and computational standpoints. In Section 5, we summarize our contributions and describe potential extensions.

2. Motivation

2.1. Literature review

Although several papers deal with maintenance scheduling in chemical industries, most previous work in the literature deals with short-term scheduling of production and maintenance (for example, Dedopoulos and Shah, 1995; Sanmartí et al., 1997; Pistikopoulos et al., 2001; Megow et al., 2011) or long-term scheduling over a multi-year horizon (Amaran et al., 2015; Cheung and Hui, 2001). As far as we know, no prior work appearing in the literature addresses what we call the medium-term turnaround problem for integrated chemical sites, let alone include the consideration of uncertainty in this context.

Several papers exist on process scheduling under uncertainty (Lin et al., 2004; Li et al., 2012; Wittmann-Hohlbein and Pistikopoulos, 2013), and fewer on maintenance considerations under uncertainty. Vujanic et al. (2012) address the robust optimization of cement plant operation, where the uncertain parameter is in the time of required reserve dispatch in the context of energy storage. A review of work in the process scheduling under uncertainty area is covered by Li and Ierapetritou (2008). A review of work in optimization under uncertainty is provided by Sahinidis (2004).

2.2. Problem description

The medium-term scheduling problem deals with refining schedules recommended by the long-term scheduling model 6–9 months in advance of a particular set of unit turnarounds. There are two primary reasons that considering the problem on such a time scale is desirable: (1) Maintenance personnel are typically hired on contract, and contract negotiation for quantity, type, and duration of manpower requirement typically begins several months prior to turnarounds; and (2) the build-up of downstream inventory, to deal with the satisfaction of product demand during the extended periods of interrupted production that turnarounds create, is known to take several weeks or even months. This provides motivation to investigate the medium-term maintenance scheduling problem, to simultaneously perform turnaround scheduling while ensuring availability of manpower of different skill sets and perform production planning across the integrated site network in preparation for disruptions in flow.

Though production planning is done by the proposed long-term turnaround planning model in Amaran et al. (2015), it is necessary to perform production planning once again after medium-term decisions have been implemented. The focus of the long-term planning model is to use long-term demand forecasts and determine frequency and alignment of turnarounds, while providing a production plan to maximize profit. However, when a set of turnarounds is 6–9 months away, we take into account uncertainty in turnaround duration. This uncertainty naturally affects production, and thus production planning has to be done once more. Once the turnarounds have taken place, the state of the plants can be updated, and so can the frequencies. This information can then be used to inform the long-term planning model, which continues to be used in the rolling horizon mode.

In summary, the main decisions to be made are the start times of each of the turnarounds, and the production and inventory decisions within the network. When considering these factors, we would like to incorporate the effect of uncertainty in our models. In this work, we focus on uncertainty in the duration of turnarounds.

From a planning perspective, several corresponding issues arise when maintenance turnarounds take longer than the nominal duration. The main issues we consider are the availability of maintenance manpower as well as the production and inventory levels over time across the entire site network. These two issues affect planning in two quite different ways.

2.2.1. Manpower

As mentioned above, maintenance personnel are typically hired on contract several months in advance for a specific time period. If maintenance exceeds the nominal duration and maintenance personnel are not available, certain maintenance activities could be deferred to future turnarounds. In addition, this could have severe impacts on production, especially in a tightly integrated site. Replacement or on-demand manpower is usually not an option due to scarcity, so there is no immediate recourse action that can be effected. As a result, the availability of manpower for the nominal duration as well as for an extended duration is paramount. Having said this, it is extremely unlikely that all the turnarounds occurring in the time window concerned are affected. These characteristics indicate that we would like to have a schedule that is robust (Ben-Tal et al., 2009) to uncertain turnaround durations with respect to manpower availability. This is discussed further in later formulations.

An example of the need for analyzing this uncertainty more closely is illustrated in Fig. 1. There are five units to be scheduled for maintenance. The maintenance durations for Units 1 and 3 are uncertain. From the point of view of production levels and demand satisfaction, the ideal situation may be, for example, to perform all of the maintenance work in the shortest time span possible in order to restore the site to normal operation quickly. However, from a robustness perspective, possible delays and consequent manpower scarcity indicate that a provision for buffer time between scheduling tasks may result in more reliable maintenance turnaround times.

In Fig. 1, Case (1) corresponds to when the assumption of exact maintenance durations is made. The optimal solution is illustrated, which keeps maximum manpower utilization at 100% of the