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Review

Integrated production scheduling and process control: A systematic review

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ABSTRACT

Production scheduling and process control have the common aim of identifying (economically) optimal operational decisions, and it is reasonable to expect that significant economic benefits can be derived from their integration. Yet, the scheduling and control fields have evolved quite independently of each other, and efforts aimed at integrating these two decision-making activities are quite recent. In this paper, we review progress made thus far in this direction. We identify key elements of control and scheduling, and carry out a systematic investigation of their use as building blocks for the formulation and solution of the integrated scheduling/control problem. On the basis of our review, we define several necessary directions for future development as well as a complement of promising applications.

Contents

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1. Introduction

Increasingly dynamic market conditions have spurred, over the past decades, significant efforts in operations research, resulting in improvements in *tactical and strategic decision-making* (i.e., production scheduling and capacity planning) in the chemical industry. Advances in numerical optimization algorithms and the decreasing cost of computer hardware have led to successful implementations of these concepts with clear economic benefits at the enterprise level (Grossmann, 2005). Concurrently, the design of chemical processes has undergone a shift towards *process integration*. Integrated processes make extensive use of material recycling and energy recovery to reduce raw material and utility demands and to lower operating costs (Westerberg, 2004; El-Halwagi, 2006). While bringing important economic benefits, process integration has a significant impact on process dynamics, giving rise to complex plant-wide interactions (Baldea and Daoutidis, 2012). This has coerced the design of *process control* systems to adopt a new, multivariable perspective, which accounts for interactions, for state and input constraints, and anticipates the effect of disturbances on the plant operation (Edgar, 2004); the most successful implementation of this new vista is Model Predictive Control (MPC) (Qin and Badgwell, 2003).

Scheduling and plant-wide control have the common aim of identifying (economically) optimal operational decisions, and it is reasonable to expect that significant economic benefits can be derived from a tighter integration or a merger of scheduling and supervisory control. Furthermore, one could ideally expect this integration process to be seamless, given that both scheduling and control rely on similar approaches (i.e., the solution of optimization problems using a process model) to accomplish their goals, and that advances in communication technology allow the relevant information to be easily shared within an enterprise. However, due to the various challenges that arose along their development, scheduling and optimal control have, in fact, evolved and continue to evolve largely independently from each other. While an exciting (and apparently easy) undertaking for academic researchers and a potential "quick win" for practitioners, the nexus of scheduling and control faces several modeling, numerical and organizational challenges (Harjunkoski et al., 2009; Shobrys and White, 2002; Engell and Harjunkoski, 2012). The development of a comprehensive theoretical solution and of a transparent framework for the practical implementation of integrated scheduling and control remain important – and still open – problems.

In this paper, we review progress made thus far in the integration of scheduling and control. With a main focus on continuous production processes, we determine the key elements of control and scheduling, and investigate their use as building blocks for the formulation and solution of the integrated scheduling/control problem. We introduce a tableau representation of these elements, which we use to create a systematic characterization of the approaches available in the literature. On the basis of our review, we identify several necessary directions for future development as well as a complement of promising applications.

2. Motivation and background

Scheduling and control systems compute and implement operating decisions over different time horizons, ranging, respectively, from several days/weeks to the order of a minute, the latter being the typical sampling and execution frequency for an MPC controller. Traditionally, the decision-making process is hierarchical (Fig. 1), with multivariable supervisory control providing the setpoints of the regulatory control layer, which in turn acts directly on the process. Scheduling calculations provide targets – possibly, but not necessarily, in the form of setpoints – for the supervisory control system.

Why is the integration of scheduling and control necessary? In the current economic environment, chemical processes must respond to many more external factors than before. These include rapid changes in the types or products that are manufactured, as well as variations in market demand for these products. Dynamic market conditions are also reflected in fluctuations in raw material and energy prices. Of particular interest in the latter category is the interaction of process systems with the power grid, where they can provide much needed demand response capacity for bridging the gap between electricity consumption and generation rates (Paulus and Borggrefe, 2011; Soroush and Chmielewski, 2013).

Under these circumstances, chemical plants must be operated in a dynamic fashion, and the time granularity of production schedules must increase (e.g., synchronizing the production of electricity-intensive processes with the operation of the grid may require that significant production rate changes be made every hour (Ierapetritou et al., 2002; Cao et al., submitted)). As a consequence, *production management decisions are made over a time scale in which process dynamics and control become highly relevant*. In this context, improving economic performance while meeting safety requirements and environmental mandates, requires exchanging

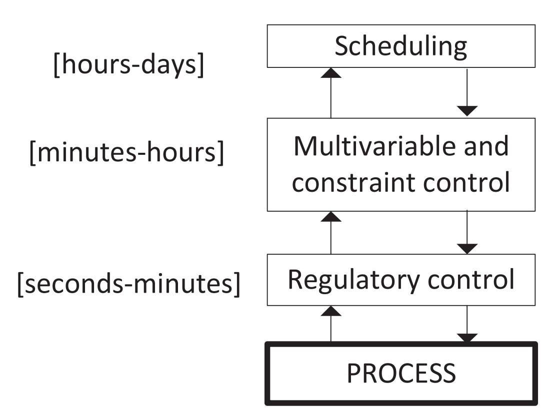

Fig. 1. The hierarchy of control decisions in the chemical enterprize. Adapted from Seborg et al. (2010).