processes

Editorial

Special Issue: Combined Scheduling and Control

John Hedengren * and **Logan Beal**

Department of Chemical Engineering, Process Research and Intelligent Systems Modeling (PRISM), Brigham Young University, Provo, UT 84602, USA; beall@byu.edu
* Correspondence: john.hedengren@byu.edu; Tel.: +1-801-477-7341

Received: 1 March 2018; Accepted: 2 March 2018; Published: 7 March 2018

This Special Issue (SI) of *Processes*, "Combined Scheduling and Control," includes approaches to formulating combined objective functions, multi-scale approaches to integration, mixed discrete and continuous formulations, estimation of uncertain control and scheduling states, mixed integer and nonlinear programming advances, benchmark development, comparison of centralized and decentralized methods, and software that facilitates the creation of new applications and long-term sustainment of benefits. Contributions acknowledge strengths, weaknesses, and potential further advancements, along with a demonstration of improvement over current industrial best-practice.

Advanced optimization algorithms and increased computational resources are opening new possibilities to integrate control and scheduling. Some of the most popular advanced control methods today were conceptualized decades ago. Over a time span of 30 years, computers have increased in speed by about 17,000 times and algorithms such as integer programming have a speedup of approximately 150,000 times on some benchmark problems. With the combined hardware and software improvements, benchmark problems can now be solved 2.5 billion times faster; i.e., applications that formerly required 120 years to solve are now completed in 5 s [1]. New computing architectures and algorithms advance the frontier of solving larger scale and more complex integrated problems. Recent work demonstrates economic and operational incentives for merging scheduling and control.

The accepted publications cover a range of topics and methods for combining control and scheduling. There were many submissions to the special issue, and about 50% were accepted for publication. The seven that were accepted have novel approaches, summary surveys, and illustrative examples that validate the methods and motivate further investigation. The articles are summarized below.

Lefebvre, D. Dynamical Scheduling and Robust Control in Uncertain Environments with Petri Nets for DESs [2].

This paper is about the incremental computation of control sequences for discrete event systems in uncertain environments through implementation of timed Petri nets. The robustness of the resulting trajectory is also evaluated according to risk probability. A sufficient condition is provided to compute robust trajectories. The proposed results are applicable to a large class of discrete event systems, in particular in the domains of flexible manufacturing.

Joglekar, G. Using Simulation for Scheduling and Rescheduling of Batch Processes [3].

This paper uses a BATCHES simulation model to accurately represent the complex recipes and operating rules typically encountered in batch process manufacturing. By using the advanced capabilities of the simulator (such as modeling assignment decisions, coordination logic, and plant operation rules), very reliable and verifiable schedules can be generated for the underlying process. Scheduling methodologies for a one-segment recipe and a rescheduling methodology for day-to-day decisions are presented.

Gupta, D.; Maravelias, C. A General State-Space Formulation for Online Scheduling [4].

This paper presents a generalized state-space model formulation particularly motivated by an online scheduling perspective, which allows for the modeling of (1) task-delays and unit breakdowns; (2) fractional delays and unit downtimes when using a discrete-time grid; (3) variable batch-sizes; (4) robust scheduling through the use of conservative yield estimates and processing times;

(5) feedback on task-yield estimates before the task finishes; (6) task termination during its execution; (7) post-production storage of material in unit; and (8) unit capacity degradation and maintenance. These proposed generalizations enable a natural way to handle routinely encountered disturbances and a rich set of corresponding counter-decisions, thereby simplifying and extending the possible application of mathematical-programming-based online scheduling solutions to diverse application settings.

Nunes de Barros, F.; Bhaskar, A.; Singh, R. A Validated Model for Design and Evaluation of Control Architectures for a Continuous Tablet Compaction Process [5].

In this work, a dynamic tablet compaction model capable of predicting linear and nonlinear process responses is successfully developed and validated. The applicability of the model for control system design is evaluated and the developed control strategies are implemented on an experimental setup. Evidence that Model Predictive Control (MPC) with an unmeasured disturbance model is the most adequate control algorithm for the studied system is presented. It is concluded that the selection of control strategies for a given compaction process is heavily dependent on real-time measurements of tablet attributes.

Beal, L.; Petersen, D.; Pila, G.; Davis, B.; Warnick, S.; Hedengren, J. Economic Benefit from Progressive Integration of Scheduling and Control for Continuous Chemical Processes [6].

This work summarizes and reviews the evidence for the economic benefit from scheduling and control integration, reactive scheduling with process disturbances, market updates, and a combination of reactive and integrated scheduling and control. This work demonstrates the value of combining scheduling and control and of responding to process disturbances or market updates. The case studies quantify the value of four phases of progressive integration and three scenarios with process disturbances and market fluctuations.

Petersen, D.; Beal, L.; Prestwich, D.; Warnick, S.; Hedengren, J. Combined Noncyclic Scheduling and Advanced Control for Continuous Chemical Processes [7].

This paper introduces a novel formulation for combined scheduling and control of multi-product, continuous chemical processes in which nonlinear model predictive control (NMPC) and noncyclic continuous-time scheduling are efficiently combined. The method uses a decomposition into nonlinear programming (NLP) and mixed-integer linear programming (MILP) problems, an iterative method to determine the number of production slots required, and a filter method to reduce the number of MILP problems required. Results demonstrate the effectiveness and computational feasibility of the approach when dealing with volatile market conditions or a large number of possible products within a short time frame.

Sahlodin, A.; Barton, P. Efficient Control Discretization Based on Turnpike Theory for Dynamic Optimization [8].

In this paper, a new control discretization approach for dynamic optimization of continuous processes is proposed. It builds upon turnpike theory in optimal control and exploits the solution structure for constructing the optimal trajectories and adaptively deciding the locations of the control discretization points. The method is most suitable for continuous systems with sufficiently long time horizons during which steady state is likely to emerge. The proposed adaptive discretization is built directly into the problem formulation, thus requiring only one optimization problem instead of a series of successively refined problems. It is shown that the proposed approach can significantly reduce the computational cost of dynamic optimization for systems of interest.

The papers from this special issue can be accessed at the following link: http://www.mdpi.com/journal/processes/special_issues/Combined_Scheduling.

As this special issue and other recent articles demonstrate, combined scheduling and control is an active area of focus in the process systems engineering community. There also remain several areas for development with optimization algorithms that converge within a controller cycle time, improved scale-up with many discrete variables (especially in MINLP), the exploitation of unique problem structures, and the utilization of strengths with emerging computing architectures. Nonlinear relationships are needed where feedback linearization or linear dynamic models are not sufficient to capture the control dynamics. Further development towards the unification of scheduling and control particularly needs industrial application with guidance on benefits and further development opportunities.

Guest Editors
John Hedengren and Logan Beal
Brigham Young University
Process Research and Intelligent Systems Modeling (PRISM) Group
Brigham Young University
Provo, Utah 84602
USA

References

1. Linderoth, J. *Overview of Mixed-Integer Programming: Recent Advances, and Future Research Directions*; FOCAPO/CPC: Tucson, Arizona, 2017.
2. Lefebvre, D. Dynamical Scheduling and Robust Control in Uncertain Environments with Petri Nets for DESs. *Processes* **2017**, *5*, 54.
3. Joglekar, G. Using Simulation for Scheduling and Rescheduling of Batch Processes. *Processes* **2017**, *5*, 66.
4. Gupta, D.; Maravelias, C.T. A General State-Space Formulation for Online Scheduling. *Processes* **2017**, *5*, 69.
5. Nunes de Barros, F.; Bhaskar, A.; Singh, R. A Validated Model for Design and Evaluation of Control Architectures for a Continuous Tablet Compaction Process. *Processes* **2017**, *5*, 76.
6. Beal, L.D.R.; Petersen, D.; Pila, G.; Davis, B.; Warnick, S.; Hedengren, J.D. Economic Benefit from Progressive Integration of Scheduling and Control for Continuous Chemical Processes. *Processes* **2017**, *5*, 84.
7. Petersen, D.; Beal, L.D.R.; Prestwich, D.; Warnick, S.; Hedengren, J.D. Combined Noncyclic Scheduling and Advanced Control for Continuous Chemical Processes. *Processes* **2017**, *5*, 83.
8. Sahlodin, A.M.; Barton, P.I. Efficient Control Discretization Based on Turnpike Theory for Dynamic Optimization. *Processes* **2017**, *5*, 85.