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Towards the integration of process design, control and scheduling: Are we getting closer?

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ABSTRACT

The integration of design and control, control and scheduling and design, control and scheduling, all have been core PSE challenges. While significant progress has been achieved over the years, it is fair to say that at the moment there is not a generally accepted methodology and/or "protocol" for such an integration – it is also interesting to note that currently, there is not a commercially available software [or even in a prototype form] system to fully support such an activity.

Here, we present the foundations for such an integrated framework and especially a software platform that enables such integration based on research developments over the last 25 years. In particular, we describe PAROC, a prototype software system which allows for the representation, modeling and solution of integrated design, scheduling and control problems. Its main features include: (i) a high-fidelity dynamic model representation, also involving global sensitivity analysis, parameter estimation and mixed integer dynamic optimization capabilities; (ii) a suite/toolbox of model approximation methods; (iii) a host of multi-parametric programming solvers for mixed continuous/integer problems; (iv) a state-space modeling representation capability for scheduling and control problems; and (v) an advanced toolkit for multi-parametric/explicit Model Predictive Control and moving horizon reactive scheduling problems. Algorithms that enable the integration capabilities of the systems for design, scheduling and control are presented on a case of a series of cogeneration units.

1. Introduction and overview

Designing economically profitable plants and improving their operational performance has been a core research field in Process Systems Engineering. The need to optimize the performance of a plant includes (i) long-term decisions, (ii) mid-term decisions and (iii) short-term decisions as well as (iv) their interactions. Therefore, a variety of computational tools has been developed for advanced model development (e.g. ASPEN Plus®, gPROMS®), – including global sensitivity analysis, parameter estimation, and mixed-integer dynamic optimization capabilities – as well as algorithms for operational scheduling procedures and advanced control methodologies.

It is generally accepted that the decisions regarding the plant design affect its operation in a most determinative manner, since they are the less likely to change while a possible change usually requires not only a considerable investment but also the permanent cease of operation; an action that affects production profit. Operational scheduling optimizes the plant performance in the mid-term while taking into account uncertainty that originates from raw material shortages, fluctuation in pricing, demand changes, equipment failure and the like. Most commonly, the operational scheduling optimization procedures are based on the assumption that the design of the plant is given and remains fixed for the entire operational horizon and that the regulatory and supervisory control of the system work flawlessly. The control strategies of a process constitute the short-term decisions in terms of operation. A variety of procedures are implemented with regulatory (P, PI, PID) control and model predictive control to be the most notable. The main burden of the controller is to reject measured and unmeasured disturbances while trying to maintain certain operation set-points imposed by the mid-term operational optimization. Table 1 presents a list of the most notable contributions on model predictive control.

The focus of the operational performance optimization has shifted from addressing the design, scheduling and control aspects individually into a combined, integrated approach. The common factor in these approaches is the effect of short-term

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Table 1
Model-based control – Indicative list.

Authors	Mode	Remarks
Campo and Morari (1987)	On-line	Min worst case ∞ norm.
Mayne and Schroeder (1997)	Off-line	Min settling time, use invariant set
Lee and Yu (1997)	On-line	Min worst case quadratic cost, use of dynamic programming for closed-loop
Scokaert and Mayne (1998)	On-line	Min worst case quadratic, invariant set for stability
Schwarm and Nikolaou (1999), Badgwell (1997)	On-line	Min nominal objective s.t. robustness quadratic/linear constraints. Large number of combinations
Kassmann et al. (2000)	On-line	Apply robustness constraints to steady state target calculation
Lee and Cooley (2000)	On-line	Min worst case quadratic cost s.t. quadratic constraints for stability
Bemporad et al. (2003)	Off-line	Min worst case -∞ norm. use of dynamic programming, solve consecutively mp-LPs
Cannon et al. (2009, 2011)	On-line	Probabilistic MPC with stochastic uncertainty & robust tube NMPC
Lee (2014)	On-line	Perspectives on robust MPC and approximate Dynamic Programming
Christofides and El-Farra (2014)	On-line	Recent advances in economic model predictive control and economic non-linear model predictive control

decision-making into mid- or long-term decisions. Therefore, numerous works have appeared in the literature throughout the past years regarding (i) the interactions of design and control and (ii) the integrated approach to scheduling and control. An indicative list of the different techniques employed to target the design and control problem is presented in Table 2. Superstructures, MIDO formulations and combinations of online optimization techniques with embedded model predictive control are worth noting. The focus of the operational performance optimization has shifted from addressing the design, scheduling and control aspects individually into a combined, integrated approach. The common factor in these approaches is the effect of short-term decision-making into mid- or long-term decisions. Therefore, numerous works have appeared in the literature throughout the past years regarding (i) the interactions of design and control and (ii) the integrated approach to scheduling and control. An indicative list of the different techniques employed to target the design and control problem is presented in Table 2. Superstructures, MIDO formulations and combinations of online optimization techniques with embedded model predictive control are worth noting.

On the other hand, recent contributions (from 2002 onwards) have opened the road to the integration of operational mid-term scheduling and control via a variety of methods. Among them, the MIDO approaches as well as the state-space scheduling problem representation with integrated online or offline model predictive control strategies are the most notable. Table 3 indicates the major contributions.

While significant progress has been achieved over the years in integrating design with control and control with scheduling, it is fair to say that at the moment there is not a generally accepted methodology and/or “protocol” for the integration of all three aspects – it is also interesting to note that currently, there is not a commercially available software [or even in a prototype form] system to fully support such an activity. In this work we present the foundations for such an integration, based on 25 years of research. We present PAROC, a prototype software system which allows for

Table 2
Integration of design and control – Indicative list.

Authors	Contributions
Lee et al. (1972)	Introduction to design and control
Narraway et al. (1991)	Steady state and dynamic economics
Brengel and Seider (1992)	Co-ordinated optimization of design and control via NMPC
Luyben and Floudas (1994)	Superstructure of design alt. into MINLP
Mohideen et al. (1996)	Economically optimal design and control
Figueroa et al. (1996), Bahri et al. (1997)	Design & control/back-off optimization and flexibility & controllability analysis in process design
Fraga et al. (2000)	Automated process synthesis/design with system dynamics consideration
Bansal et al. (2000, 2002)	MIDO approach, PI control schemes
Van Schijndel and Pistikopoulos (2000)	Review on process design and operability
Kookos and Perkins (2001)	Bouncing scheme to reduce the relaxed design and control problem size
Lewin et al. (2002)	On the consideration of advanced control in the design optimization
Sakizlis et al. (2003, 2004)	Simultaneous mpMPC and online design optimization. Case studies on binary distilation column and evaporator
Seferlis and Georgiadis (2004)	The integration of design and control
Gani (2004), Hamid et al. (2010)	Review on design & control and model-based methodology for the integration of design and control
Olsen et al. (2005)	Control interactions with a vinyl acetate process process design
Malcolm et al. (2007)	Framework for design & control
Flores-Tlacuahuac and Biegler (2007)	MIDO for the simultaneous design and control problem solution
Ricardez-Sandoval et al. (2009)	Literature review on design and control integration
Würth et al. (2011)	Dynamic optimization and NMPC
Yuan et al. (2012)	Review on design and control
Ricardez-Sandoval (2012), Sánchez-Sánchez and Ricardez-Sandoval (2013)	Probabilistic & robust approach to optimal design and control
Gebreslassie et al. (2012)	Design under uncertainty via multi-objective optimization
Liu et al. (2013)	Trade offs between design & operation
Washington and Swartz (2014)	Multiperiod, parallel, mixed integer dynamic optimization
Diangelakis et al. (2014)	Sequential design optimization and mp-MPC. Application on a residential cogeneration systems
Chi et al. (2015)	Design optimization with data-driven control schemes
Vega et al. (2014a,b)	Review, classification and example of integrated design and control
Gutierrez et al. (2014)	Control structure selection for an MPC-based approach

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