Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 1997–2004

# Integrated control and process design in CFB boiler design and control – application possibilities

Matias Hultgren*,
Enso Ikonen*, Jenö Kovács**

*University of Oulu, Systems Engineering
P.O. Box 4300, FI-90014 University of Oulu, Finland (e-mail: firstname.lastname@oulu.fi).
**Amec Foster Wheeler R&D
Relanderinkatu 2, P.O. Box 201, FI-78201 Varkaus, Finland (email: jeno.kovacs@amecfw.com)

**Abstract:** Integrated control and process design (ICPD) practices focus on an interaction between process and control design. The paper investigates ICPD design in circulating fluidized bed (CFB) power plants, which face increasing load change, efficiency and emission requirements. The state of ICPD research is examined and a classification of its methodologies is provided. The applicability of ICPD to large-scale CFB boilers is discussed for the first time based on this classification. Two ICPD case studies with a simple steam path mass storage model are presented for an industrial CFB boiler, with the aim of illustrating possibilities and challenges related to boiler ICPD. The steam mass storage amounts of the boiler superheating and evaporation sections are modified based on the dynamic relative gain array and closed-loop process optimization to generate processes with improved constant pressure mode output power setpoint tracking performance.



*Keywords:* Power plant control system design, Interaction between design and control, Circulating fluidized bed boiler, Power plant simulation, Control of large-scale systems, Process optimization.

## 1. INTRODUCTION

The paper investigates integrated control and process design (ICPD) in the circulating fluidized bed boiler (CFB). In ICPD, the process and its control system are designed at the same time, so that control requirements affect the process, and process dynamics become better incorporated into the control (Fig. 1). This gives improved closed-loop responses, and design decisions with negative dynamic effects can be avoided. The approach differs from conventional sequential design, where the process is designed based on steady-state goals, and control is designed after this to satisfy stability and dynamic performance criteria. This limits achievable control performance by the open-loop dynamics from process design.

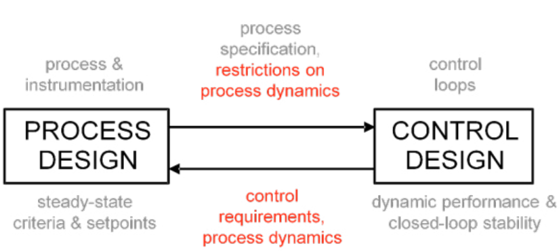


Fig. 1. Process and control design interaction in ICPD.

A deeper interaction between process and control design is needed for steam boilers, which currently face many control design challenges. While combustion power plants were previously mainly operated at constant load, nowadays they are facing fast and frequent load transitions with accurate $MW_e$ setpoint tracking demands, as well as extended partial load operation periods. Power generation efficiency needs to be maximized, which is reflected as complicated flowsheets and extreme operating conditions. In CFB plants, increasing boiler sizes and technologies like carbon capture and storage (CCS) have introduced new requirements. The ICPD problem gains another dimension in utility power plants that supply power to a process, but also operate in a power grid (Chen & Bollas 2017, Dowling & Zavala 2017).

This paper examines how ICPD can be applied to CFB boiler design. General features of ICPD are outlined and its main approaches are classified. ICPD design is also demonstrated with an industrial CFB boiler steam path model. Available ICPD approaches need to be outlined for boiler design, since the topic spans a wide range of design practices. The review of Huusom (2015) should be noted, as it similarly focuses on the challenges and opportunities of ICPD in industry.

Few ICPD studies have been carried out for combustion power plants. Diangelakis & Pistikopoulos (2016) performed ICPD for a small scale cogeneration plant, considering the combustor size and PID controller parameters. The work has also been extended to scheduling and model-based control (Diangelakis et al. 2017). Chen & Bollas (2017) determined air preheating and main steam temperature setpoints together with supervisory control for a chemical looping–combined cycle plant. ICPD presents major possibilities for large-scale boilers, which forms the motivation for the present work. Previous ICPD work for heat exchanger networks and power grids offers a starting point for the design (e.g. Adeodu & Chmielewski 2017, Alhammadi & Romagnoli 2004), but these findings can't be applied directly to boiler control.

2405-8963 © 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.180

The paper is structured as follows. Chapter 2 introduces the CFB boiler and its control tasks. Chapter 3 presents a basic classification of ICPD approaches, which is elaborated on for process knowledge and mathematical programming ICPD in chapters 4 and 5, together with the design examples for the CFB steam path. Chapter 6 presents the conclusions.

## 2. CFB PROCESS & CONTROL

In fluidized bed boilers (Fig. 2), fuel particles are fluidized and combusted in a bed of incombustible material by the input primary and secondary gas flows (Basu 2006). In the circulating fluidized bed setup (CFB), particles leave the furnace with the gas flows. The solids are separated and returned to the furnace, while the flue gas goes to the flue gas duct. The input gas is usually air, but in the oxy combustion CCS setup a mix of recirculated flue gas and pure $O_2$ is used.

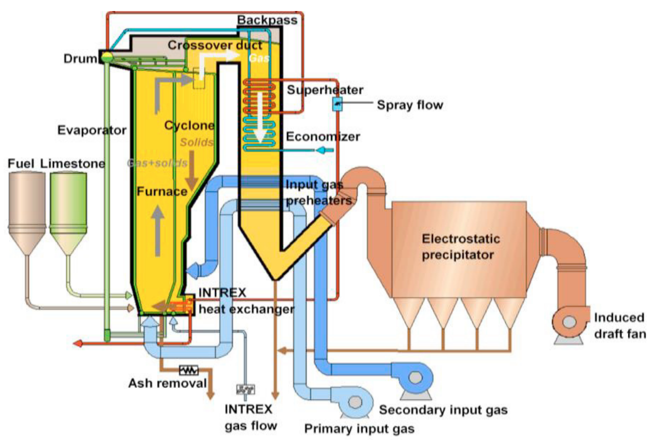


Fig. 2. Operational schematic figure of a drum CFB boiler (modified from Hultgren et al. 2014).

Combustion heat is used to generate steam in the steam path. Feedwater is evaporated in the furnace evaporator. The steam is superheated to form main steam in a block of superheaters (SH), with cooling desuperheater (DSH) spray flows between the stages. The steam expands in the turbine to generate power. In drum boilers, water is separated from steam after the evaporator. Once-through (OTU) boilers generate steam in a "once-through" pass with no separation stage. The setup enables supercritical and sliding-pressure operation, but it also leads to control challenges, as there is a connection between the feedwater and the main steam, and as the steam storage capacity is small. (Joronen et al. 2007, Klefenz 1986)

The control objectives of a power plant are to maintain the generated power at its setpoint and to maximize boiler efficiency. The main individual control tasks are feedwater flow control, main steam temperature and pressure control, combustion control, turbine-generator unit control (output $MW_e$, frequency and voltage) and furnace pressure control (Joronen et al. 2007, Klefenz 1986). The unit master control strategy determines how the main steam pressure and $MW_e$ output controls are coordinated. In turbine-following control, the $MW_e$ is adjusted with the boiler firing power, and the steam pressure is controlled with the turbine valve. In boiler-following control, the opposite control pairings are used.

## 3. INTEGRATED CONTROL & PROCESS DESIGN

### *3.1 ICPD features*

On a broad scale, ICPD involves all processing sequence, flowsheet, equipment sizing, control topology and controller design decisions of the process. An ICPD methodology can be characterized based on how these decisions are formulated and how they interact with each other. Important questions are what the goals for the increased design stage interaction are, how extensive it should be and how it is implemented.

A classification of the features of ICPD is given in Table 1, which is a novel contribution of this work. In sections 3.2–3.4, some aspects of Table 1 are discussed for CFB design. The main grouping is made between process knowledge and mathematical programming (chapters 4–5). Alternative ICPD reviews have been presented e.g. by Perkins & Walsh (1996), Ricardez-Sandoval et al. (2009), Sakizlis et al. (2004), Sharifzadeh (2013), Vega et al. (2014a) and Yuan et al. (2012). An emerging ICPD-related field is integrated scheduling and control (Baldea & Harjunkoski 2014, Dowling & Zavala 2017). Although the topic has even been studied for thermal power plants (Bindlish 2017, Diangelakis et al. 2017), scheduling is out of scope for this paper. ICPD is similarly often connected to process integration in literature.

**Table 1. General features and characteristics of integrated control and process design (ICPD) methodologies.**

| **Integrated control and process design** | | |
|---|---|---|
| *Problem definition* | *Design structure* | *Methodology basis* |
| **Performance evaluation**<br>○ Economic & environmental<br>○ Thermodynamic analysis<br>○ Disturbance rejection & setpoint tracking<br>○ Relevant process properties for control | **Degree of interaction**<br>○ "Anticipating" sequential (Meeuse & Grievink 2004)<br>○ Partially integrated<br>○ Fully integrated | **Process knowledge ICPD**<br>○ Heuristics<br>○ Phenomenon based<br>○ System analysis based |
| **Purpose**<br>○ Find best achievable performance<br>○ Improve dynamics through design<br>○ Generate best process+control system | **Decomposition**<br>○ Hierarchy of connected design steps<br>○ Decomposition method<br>○ "Closed" input–output design framework | **Mathematical programming ICPD**<br>○ Controllability based optimization<br>○ Full dynamic optimization, MIDO<br>○ Embedded control optimization<br>○ Robust optimization<br>○ Back-off optimization<br>○ Multi-objective optimization<br>○ Stochastic/probabilistic optimization |
| **Scope**<br>○ Continuous or discrete decisions<br>○ Dynamic or steady-state operation<br>○ Process or control design basis | **Control design**<br>○ Adapt control template to process<br>○ Plantwide control design<br>○ Model-based control ICPD | |

### *3.2 Scope and structure*

The scope of CFB boiler ICPD should be on the entire plant, as the process is a cyclic network of connected units with overlapping control tasks and process interactions. This is emphasized in the OTU steam path with its steam pressure, steam temperature and feedwater control interactions. Thus, design results for control tasks like superheater temperature control are ultimately relevant only on a plantwide scale.

In ICPD, operational decisions concern continuous variables (e.g. unit sizing, controller tuning), while structural decisions are discrete (flowsheet, control loops). The controller type and process structure are often predefined (Sharifzadeh 2013), and ICPD focuses on continuous process parameters and control connections between manipulated (MV) and controlled (CV) variables. This applies to boilers: flowsheets are mostly based on convention and PID control is prevalent.

The starting point for ICPD is often an existing process and/or control structure that is modified by the design. CFB examples include the application of drum-CFB control to the OTU-CFB, and oxy-CFB control design based on air-fired control (Hultgren et al. 2014). Standard CFB setups can be obtained from literature (Basu 2006, Joronen et al. 2007, Klefenz 1986). The main source of design variability is the amount and placement of SH units and DSH sprays, as the evaporator and many preheaters have “fixed” positions in the boiler. The three-superheater system is a common example.

ICPD principally aims at optimal steady-state or dynamic operation. If optimal dynamic performance with feasible economics is desired (e.g. load-following boilers), accurate dynamic modelling is needed during early design stages. Similarly, ICPD is usually based on tools and practices from either control or process design. Due to its transient-oriented design requirements, CFB ICPD should focus on control.

### *3.3 Design goals and performance evaluation*

The most crucial property of an ICPD methodology is how desirable closed-loop performance is defined.

- **Economics:** Balance between capital (process) and operating costs (process and control), revenue vs. costs.
- **Thermodynamics:** Energy and exergy efficiency, “first-principles” chemical/physical approach.
- **Control:** Dynamic simulation with chosen disturbances, stability and minimal reference trajectory error.
- **System analysis:** Process properties relevant for control, indicates good performance or need for advanced control.

CFB boiler economics should consist of annualized fuel and investment costs, scaled with the generated $MW_e$. Quality related ICPD (e.g. Elliott & Luyben 1995) can’t necessarily be used directly for the output power/frequency, but a penalty for setpoint deviations should be included. Environmental performance mainly depends on steady-states. Efficiency, exergy and heat rate analysis can also be used in boiler ICPD design (Bindlish 2017, Chen & Bollas 2017, Ray et al. 2010).

Load setpoint tracking is emphasized in boiler design, except when the plant is predominantly used for base load operation. Setpoint tracking is studied in ICPD with dynamic error based measures like the integral square (ISE) or absolute (IAE) error (e.g. Ekawati 2003). Nonlinearity also needs to be analyzed due to the complex boiler dynamics, using e.g. linear error norms, bifurcation analysis or optimal control law (Kiss et al. 2007, Schweickhardt & Allgöwer 2004).

Control design properties that are utilized in ICPD include controllability and its various definitions, switchability, flexibility, operability, resiliency, and robustness (Bahri et al. 1997, Bogle et al. 2004, Ekawati 2003, Engell et al. 2004, Sharifzadeh 2013, Weitz & Lewin 1996). Switchability, i.e. the ability to move feasibly between operating points, should especially be considered in load-following boilers. Common analysis methods are the eigenvalue and singular value decomposition, the condition number, and different relative gain array (RGA) modifications like the dynamic RGA (DRGA), the partial relative gain (PRG, Häggblom 1997), the performance-RGA (Skogestad & Postlethwaite 2005) and the block relative gain (BRG, Manousiouthakis et al. 1986). These metrics can be used for studying interactions, stability, disturbance sensitivity and robustness in the CFB boiler.

### *3.4 Control design framework*

Because of its procedural nature, control-oriented design and plantwide focus, ICPD is related to plantwide control, which aims at defining an overall control strategy for an entire plant of connected units (Skogestad 2004). The focus is on the selection of MVs, CVs and measurements, as well as on their control connections. In the CFB, plantwide control should be utilized for upper level solutions like unit master control, or for complex tasks like combustion control (Niva et al. 2015).

Model-based control has recently gained significant interest in ICPD research (Huusom 2015). As the control algorithm is based on the open-loop system, the controller can be linked to process changes in a closed framework, and discrete MV–CV connection variables are not needed. MPC ICPD has been studied e.g. by Bahakim & Ricardez-Sandoval (2014), Brengel & Seider (1992), Chawankul et al. (2007), Francisco et al. (2011) and Gutierrez et al. (2014). Especially economic model-based control could enable a joint process-controller optimization with one economic objective, like in the EMPC/ ELOC based approach of Adeodu & Chmielewski (2017) for power grid energy storage. The applicability of MPC in CFB boiler ICPD is affected by how well suitable controller models can be constructed for the plantwide boiler flowsheet.

## 4. PROCESS KNOWLEDGE BASED ICPD

### *4.1 General principles*

Process knowledge oriented ICPD uses modelling and operational knowledge from the process to guide the design decision-making. The simplest way to do this is to use a process model during the design to verify that decisions do not lead to reduced control performance (for steam boilers e.g. Majanne & Maasalo 2009). However, this approach requires many simulations, and results are easily obscured by overlapping effects and modelling assumptions. Systematic process knowledge oriented ICPD is thus often preferable.

Process knowledge ICPD has three modes: identification of design choices that cause control bottlenecks, design of open-loop systems that are inherently "easy" to control, and system classification based on selected criteria. Process knowledge ICPD is able to address design issues that would be difficult to define in formal algorithms, and there is an active interaction with the designer. The approach is particularly useful for screening candidate solutions for further analysis.

The downsides of process knowledge ICPD are that the design is often unable to manage multiple tasks effectively, optimality is hard to ensure, and solution templates easily lead to conservative designs. Connecting design parameters to process performance might also be limited for black-box systems, and first-principles models often have high computational costs for large flowsheets like steam boilers.

### *4.2 Methods*

Process knowledge ICPD can be separated into heuristic design rules and systematic process characterization. While heuristics are easy to implement, they are strictly rule-based and inflexible. Moreover, while process and control design heuristics for individual boiler units like heat exchangers are readily available, plantwide design aspects are often ignored.

A process can be characterized through its chemical/physical phenomena or through control oriented analysis (Vega et al. 2014a). In phenomenon based analysis, thermodynamic properties are linked to control performance, considering energy, mass and momentum balances, generation terms, and driving forces (e.g. Alhammadi & Romagnoli 2004, Bogle et al. 2004, Hamid 2011, Meeuse & Grievink 2004). This approach has significant potential for power plant ICPD. The physical reasons for the non-minimum phase "shrink" and "swell" behaviour in drum boilers (Åström & Bell 2000) is a good example of phenomenon oriented control design. Similarly, Hultgren et al. (2015, 2014) defined how air-fired CFB control should be modified for oxy-firing based on the flowsheet and the properties of the combustion atmosphere.

In system analysis based characterization, system behaviour is evaluated through lower-complexity (linear) models, using common or custom performance indices for the properties in section 3.3 (e.g. Alhammadi & Romagnoli 2004, Bogle et al. 2004, Ekawati 2003, Engell et al. 2004, Weitz & Lewin 1996). For example, Skogestad & Postlethwaite (2005) outlined an approach for input-output controllability, using sensitivity, pole-zero, minimum singular value, RGA and condition number analysis. Indeed, ICPD design approaches are often combinations of different methods, such as the process characterization cube of Hernjak et al. (2004).

Controllability and interactions are central topics in the CFB, especially for the OTU boiler. Steam temperature control with multiple DSH sprays can result in ill-conditioning, and similar issues can be encountered for the primary and secondary oxidant flows (Hultgren et al. 2015). Relative gain analysis is well-suited for this design purpose. The analysis should be performed in the dynamic domain (DRGA), and the large dimensionality of the CFB flowsheet might require RGA modifications like the PRG or BRG. The BRG was used for boiler temperature control by Manousiouthakis et al. (1986). Hultgren et al. (2015) employed the PRG for oxy-CFB plantwide control structure design and process interaction analysis. Maffezzoni et al. (1985) used control tools like Nyquist plots for solar power plant ICPD.

### *4.3 Case study: steam path DRGA design*

System analysis in CFB boiler ICPD can be demonstrated with the DRGA and a simple steam path model that describes the relation between steam pressure, steam flow and the turbine $MW_e$ output. It consists of first-order blocks for the evaporation, superheating and turbine sections derived from (1)–(2), where section sizes are represented by time constants ("mass storage coefficients") (Doležal & Varcop 1970). The resulting 2×2 transfer function model has the boiler load and turbine valve as MVs, and the main steam pressure and output $MW_e$ as CVs. The evaporation and superheating mass storages TE and TS are modified, and the resulting DRGAs are calculated as a function of frequency (Fig. 3).

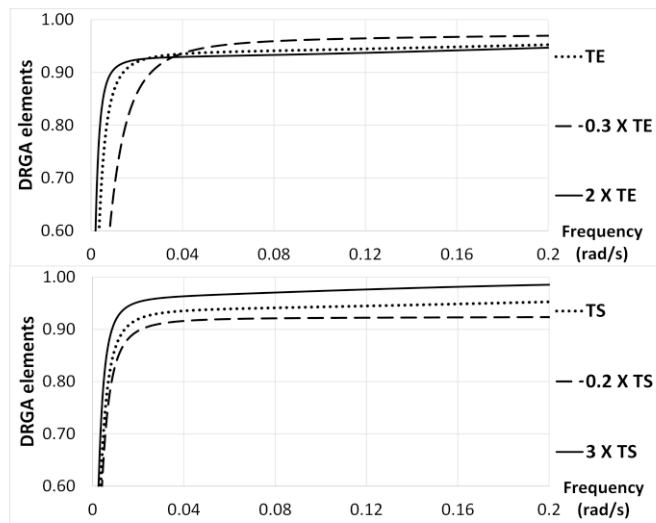


Fig. 3. DRGA elements of boiler-following control connections for evaporator (TE) and superheater (TS) sizes.

$$\frac{dp}{dt} = \frac{1}{C}\left(m_{S,in} - m_{S,out}\right), \tag{1}$$

$$\Delta p = f\,\frac{m_{S,out}}{\rho_S}, \tag{2}$$

where $C$ is mass storage (TE/TS), $p$ is pressure, $m_S$ is steam mass flow, $\rho_S$ is steam density and $f$ is a pipe friction factor.

Based on the DRGA, a large superheating mass storage TS leads to improved controllability, as stored steam between the turbine and the evaporator increases the decoupling between $MW_e$ and pressure control. Increasing the evaporating section size (TE) also improves controllability at low frequencies, but above 0.04 rad/s the situation is reversed, which could be explained by the evaporator and superheater size differences. The findings are visible as $MW_e$ control performance during output power setpoint changes (Table 2), using tightly tuned boiler-following PI control (turbine valve–output $MW_e$, main steam pressure–boiler load loops) at constant steam pressure.

**Table 2. $MW_e$ setpoint error during a triangular ±5 % $MW_e$ setpoint disturbance, normalized by largest error.**

| Ramp speed (s) | | 500 | 200 | 100 | 80 | 60 | 40 | 20 | 15 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| TS, $MW_e$ error | TS | 1.00 | 0.98 | 0.97 | 0.97 | 0.98 | 0.99 | 0.99 | 0.99 | 0.98 |
| | 0.2×TS | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 3×TS | 0.98 | 0.92 | 0.90 | 0.92 | 0.94 | 0.96 | 0.97 | 0.97 | 0.96 |
| TE, $MW_e$ error | TE | 0.86 | 0.72 | 0.78 | 0.86 | 0.93 | 0.99 | 0.99 | 0.99 | 1.00 |
| | 0.3×TE | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.97 | 0.98 |
| | 2×TE | 0.83 | 0.62 | 0.73 | 0.83 | 0.92 | 0.99 | 1.00 | 1.00 | 1.00 |

## 5. MATHEMATICAL PROGRAMMING BASED ICPD

### *5.1 General principles*

Mathematical programming ICPD defines the problem in a formal mathematical framework and searches for solutions systematically within it using an optimization algorithm. All approaches can essentially be derived from the basic problem statement "F" (3)–(4) (Hamid 2011, Sakizlis et al. 2004).

$$\min_{x,y,u} F(\boldsymbol{x'},\boldsymbol{x},\boldsymbol{y},\boldsymbol{u}) = \begin{bmatrix} F_1(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u}) \\ F_2(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u}) \end{bmatrix}, \tag{3}$$

$$\begin{cases} f(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},t)=0 \\ h(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u})=0 \\ g(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u})\geq 0 \\ \boldsymbol{x}^L \leq \boldsymbol{x} \leq \boldsymbol{x}^U \\ \boldsymbol{x}(t_0)=\boldsymbol{x}_0 \\ \boldsymbol{u}(t_0)=\boldsymbol{u}_0 \end{cases}, \tag{4}$$

where $\boldsymbol{x}$ are states, $\boldsymbol{y}$ and $\boldsymbol{u}$ are process and design variables, $t$ is time, $F_1$ is economic objective, $F_2$ is control objective, $f$ are process equality constraints, $h$ are performance equality constraints, g are performance inequality constraints, "$L$"/"$U$" are lower/upper bounds, and "0" denotes initial conditions.

The setup of a mathematical programming ICPD approach largely depends on which design decisions are included in the problem, most importantly the need for dynamic optimization and discrete decisions. Structural decisions are formulated as mixed-integer (MILP or MINLP) problems, where the design progression is characterized by the chosen mixed-integer solver (Grossmann 2002). Likewise, ICPD can be performed either in the open-loop or the closed-loop. Methodologies are usually restricted to set controller types (Yuan et al. 2012), although research has aimed at including different controllers into the same formulation through perfect control, inverse optimality or controller parameterization (Alvarez et al. 2004, Lear et al. 1995, Perkins & Walsh 1996, Sharifzadeh & Thornhill 2013, Swartz 2004). Closed-loop design should include the controller parameters into the optimization to make different process setups comparable. As CFB boiler ICPD aims at improving load transitions, dynamic closed-loop optimization will be necessary at least to some extent.

The design goal is formed as a single economic objective or a set of goals, including dedicated control performance and controllability measures. The tradeoff between economic and control objectives can be formulated as a weighted sum, but as making objectives comparable is challenging, ICPD often relies on multi-objective optimization (Alhammadi & Romagnoli 2004, Ekawati 2003, Egea et al. 2007, Schweiger & Floudas 1998, Sharifzadeh & Thornhill 2013, Vega et al. 2014b). Stochastic and probabilistic approaches are used for global optimization of difficult nonconvex IPCD problems (Bahakim & Ricardez-Sandoval 2014, Sendin et al. 2004). Defined disturbance scenarios and uncertainties also greatly affect the results of ICPD optimization. CFB design should center on fuel, air and feedwater disturbances for base load operation and load demand ramps for load-following boilers.

Mathematical programming ICPD is effective at locating optimal and unconventional solutions, but it also results in difficult calculation problems and poor convergence for large flowsheets. This is a limitation for thermal power plants, where a plantwide perspective is preferable. "Optimal" results might also not be applicable in real life (Alvarez et al. 2004). In fully simultaneous design, separating the effects of control and process design decisions can also be difficult.

### *5.2 Methods*

The simplest way to implement mathematical programming based ICPD is to incorporate control performance measures to process optimization as constraints or cost function terms (e.g. Francisco et al. 2011, Vega et al. 2014b, Yuan et al. 2012), forming a tradeoff between economics and control. Control indices easily result in local optima, non-convexities and multiplicities in the cost function (Egea et al. 2007, Schweiger & Floudas 1998). This has to be considered for design goal definitions in transient-driven CFB design.

In dynamic optimization, ICPD is carried out with a dynamic model and a single economic objective, considering process and control design together from the start. Especially the comprehensive mixed-integer dynamic optimization (MIDO) approach has attracted interest (Bahri et al. 1997, Bansal et al. 2000, Flores-Tlacuahuac & Biegler 2008, Miranda et al. 2008, Mohideen et al. 1997, Sakizlis et al. 2004, Terrazas-Moreno et al. 2008). A MIDO is solved by converting it into a MINLP through simultaneous, sequential or hybrid discretization (Sharifzadeh 2013). MIDO design is limited by its high computational requirements for large industrial CFB flowsheets. MIDO was used for combustion power plants by Diangelakis et al. (2017) and Diangelakis & Pistikopoulos (2016). Dynamic optimization was also employed in the efficiency oriented boiler ICPD of Chen & Bollas (2017).

Embedded control optimization casts the dynamic ICPD task as an iterative bi-level framework (Moon et al. 2011, Yuan et al. 2012). The outer level looks for design parameters that govern the dynamics with a first-principles model. The inner level tests the dynamic performance with state-space models based on outer level design decisions. Deshmukh & Allison (2013) utilized a similar approach for wind turbine ICPD.

In robust optimization ICPD, robust control tools are used for evaluating stability and flexibility by describing the system with low-order models with uncertainty (Chawankul et al. 2007, Grosch et al. 2008, Mönnigmann & Marquardt 2002, Ricardez-Sandoval et al. 2009). Robust ICPD is divided into Lyapunov linear matrix inequality and structured singular value methods (Ricardez Sandoval 2008). The focus on worst-case disturbances easily leads to conservative designs.

In back-off optimization, the starting point of the design is a steady-state process optimum with control. The system dynamics are examined together with disturbances to find the process variability region, and the operating point is "backed off" from system constraints accordingly. The minimization of the back-off penalty leads to the optimal dynamic operating point (Kookos & Perkins 2004, Yuan et al. 2012). The approach is quite limited for load-following CFB design, as load change disturbances would require a large back-off, but it could be considered e.g. for steam temperature control.

### *5.3 Case study: closed-loop steam path optimization*

ICPD optimization can be demonstrated with the chapter 4.3 steam path model. Boiler-following PID control is applied for the main steam pressure and output power, with tight tuning for the $MW_e$ controller. The pressure controller parameters are then optimized together with the superheater storage TS to minimize the pressure control error in constant pressure operation. The process is excited with two fast output $MW_e$ setpoint ramps. The cost function is the steam pressure IAE error, and the optimization is performed with the Nelder-Mead algorithm. The results are compared to optimal PID parameters for the original TS mass storage (Fig. 4).

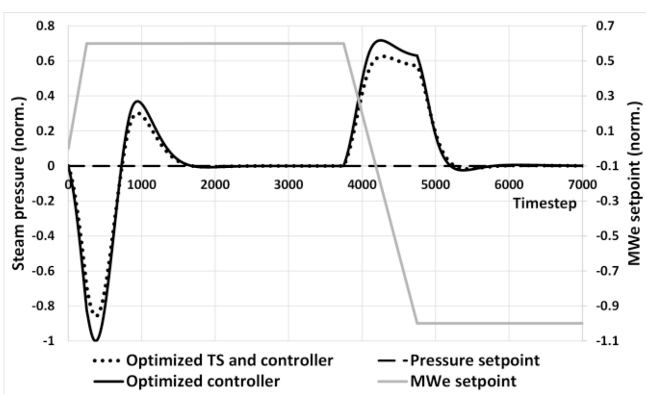


Fig. 4. Boiler-following steam pressure control for $MW_e$ setpoint ramps. Optimized PID parameter base case (minimal pressure tracking error) vs. ICPD case with optimized superheating mass storage TS and PID controller parameters.

The optimization successfully determined the TS storage and modified the pressure controller parameters accordingly. At constant pressure, a large superheater enables accurate steam pressure control and also slightly improved $MW_e$ control (Table 3), as was also indicated by the DRGA in section 4.3. However, when the optimization is run in sliding-pressure mode ($MW_e$ and pressure setpoints change according to load level), a small superheating section gives the most effective pressure control. The loop decoupling suggested by the DRGA is thus overshadowed by the fast dynamics of a small steam storage. Moreover, including the $MW_e$ controller and a $MW_e$ setpoint tracking objective into the optimization resulted in local optima, since TS mainly affects the steam pressure response. Indeed, fast $MW_e$ control with the turbine valve can basically be achieved for any superheater size.

**Table 3. Optimal ICPD results for constant and sliding pressure $MW_e$ ramps, normalized by optimized PID controller base case. DN = derivative PID filter.**

| | P | I | D | DN | TS | p IAE | $MW_e$ IAE |
|---|---|---|---|---|---|---|---|
| Constant pressure | 1.12 | 1.12 | 1.12 | 0.43 | 2.00 | 0.87 | 0.97 |
| Sliding pressure | 1.20 | 1.01 | 2.12 | 4.53 | 0.50 | 0.97 | 0.99 |

## 6. CONCLUSIONS

Steam boiler control is a specific field with requirements that differ from many other chemical processes: strong loop interactions, a wide range of operating points, and a focus on load transition performance. Based on literature, integrated control and process design (ICPD) is useful for improving load change speed in circulating fluidized bed (CFB) power plants. Almost no ICPD studies exist for large-scale boilers, and as ICPD is a wide research field, a review of its approaches was provided here, focusing on CFB design.

Both process knowledge and mathematical programming ICPD is basically applicable to the CFB. Phenomenon based process characterization is a good starting point, as it can use existing design knowledge, and as dynamic optimization, in particular, is computationally heavy for the CFB flowsheet. Phenomenon based boiler analysis constitutes the steam thermodynamics, combustion reactions and heat transfer.

ICPD design was demonstrated on an industrial CFB steam path model. Evaporation and superheating mass storages were modified through DRGA analysis and closed-loop optimization to generate improved load changes. However, the cases also highlighted challenges related to the chosen optimization objective formulation and analysis methods.

## REFERENCES

Adeodu, O. and Chmielewski, D.J. (2017). Optimal Sizing and Placement of Grid-level Energy Storage. In *FOCAPO/CPC 2017 conference*, Tucson, USA, Jan 8–12.

Alhammadi, H.Y. and Romagnoli, J.A. (2004). Process design and operation: Incorporating environmental, profitability, heat integration and controllability considerations. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 264–305. Elsevier, Amsterdam.

Alvarez, J., Zaldo, F. and Oaxaca, G. (2004). Towards a joint process and control design for batch processes: application to semibatch polymer reactors. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 604–634. Elsevier, Amsterdam.

Bahakim, S.S. and Ricardez-Sandoval, L.A. (2014). Simultaneous design and MPC-based control for dynamic systems under uncertainty: A stochastic approach. *Comput. Chem. Eng.*, 63, 66–81.

Bahri, P.A., Bandoni, J.A. and Romagnoli, J.A. (1997). Integrated flexibility and controllability analysis in design of chemical processes. *AIChE J.*, 43(4), 997–1015.

Baldea, M. and Harjunkoski, I. (2014). Integrated production scheduling and process control: A systematic review. *Comput. Chem. Eng.*, 71, 377–390.

Bansal, V., Perkins, J.D., Pistikopoulos, E.N., Ross, R. and van Schijndel, J.M.G. (2000). Simultaneous design and control optimisation under uncertainty. *Comput. Chem. Eng.*, 24(2–7), 261–266.

Basu, P. (2006). *Combustion and Gasification in Fluidized Beds*. CRC Press, Taylor & Francis Group, Boca Raton.

Bindlish, R. (2017). Scheduling, Optimization and Control of Power for Industrial Cogeneration plants. In *FOCAPO/CPC 2017 conference*, Tucson, USA, Jan 8–12.

Bogle, I.D.L., Ma, K., Hagemann, J. and Fraga, E.S. (2004). Analysing the controllability of nonlinear process systems. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 168–186. Elsevier, Amsterdam.

Brengel, D.D. and Seider, W.D. (1992). Coordinated design and control optimization of nonlinear processes. *Comput. Chem. Eng.*, 16(9), 861–886.

Chawankul, N., Ricardez Sandoval, L.A., Budman, H. and Douglas, P.L. (2007). Integration of Design and Control: A Robust Control Approach Using MPC. *Can. J. Chem. Eng.*, 85(4), 433–446.

Chen, C. and Bollas, G.M. (2017). Semi-batch Chemical-looping Reactors Integrated with Combined Cycle Power Plants Operating at Transient Electricity Demand. In *FOCAPO/CPC 2017 conference*, Tucson, USA, Jan 8–12.

Deshmukh, A.P. and Allison, J.T. (2013). Simultaneous Structural and Control System Design for Horizontal Axis Wind Turbines. In *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,* Boston, USA, Apr 8–11.

Diangelakis, N.A., Burnak, B. and Pistikopoulos, E.N. (2017). A multi-parametric programming approach for the simultaneous process scheduling and control – Application to a domestic cogeneration unit. In *FOCAPO/CPC 2017 conference*, Tucson, USA, Jan 8–12.

Diangelakis, N.A. and Pistikopoulos, E.N. (2016). Modelling, Design and Control Optimization of a Residential Scale CHP System. In Kopanos, G.M., Liu, P. and Georgiadis, M.C. (ed.), *Advances in Energy Systems Engineering*, 475–506. Springer, Cham.

Doležal, R. and Varcop, L. (1970). *Process Dynamics, Automatic Control of Steam Generation Plant*. Elsevier, Amsterdam.

Dowling, A.W. and Zavala, V.M. (2017). Redesigning Decision-making Architectures to Exploit Multi-scale Electricity Markets. In *FOCAPO/CPC 2017 conference*, Tucson, USA, Jan 8–12.

Egea, J.A., Vries, D., Alonso, A.A. and Banga, J.R. (2007). Global Optimization for Integrated Design and Control of Computationally Expensive Process Models. *Ind. Eng. Chem. Res.*, 46(26), 9148–9157.

Ekawati, E. (2003). *The Development of Systematic Controllability Assessment for Process Control Designs*. Murdoch University, Perth.

Elliott, T.R. and Luyben, W.L. (1995). Capacity-Based Economic Approach for the Quantitative Assessment of Process Controllability during the Conceptual Design Stage. *Ind. Eng. Chem. Res.*, 34(11), 3907–3915.

Engell, S., Trierweiler, J.O., Völker, M. and Pegel, S. (2004). Tools and indices for dynamic I/O-controllability assessment and control structure selection. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 430–463. Elsevier, Amsterdam.

Flores-Tlacuahuac, A. and Biegler, L.T. (2008). Integrated control and process design during optimal polymer grade transition operations. *Comput. Chem. Eng.*, 32(11), 2823–2837.

Francisco, M., Vega, P. and Álvarez, H. (2011). Robust Integrated Design of processes with terminal penalty model predictive controllers. *Chem. Eng. Res. Des.*, 89(7), 1011–1024.

Grosch, R., Mönnigmann, M. and Marquardt, W. (2008). Integrated design and control for robust performance: Application to an MSMPR crystallizer. *J. Proc. Control*, 18(2), 173–188.

Grossmann, I.E. (2002). Review of Nonlinear Mixed-Integer and Disjunctive Programming Techniques. *Optim. Eng.*, 3(3), 227–252.

Gutierrez, G., Ricardez-Sandoval, L.A., Budman, H. and Prada, C. (2014). An MPC-based control structure selection approach for simultaneous process and control design. *Comput. Chem. Eng.*, 70, 11–21.

Hamid, M.K.A. (2011). *Model-Based Integrated Process Design and Controller Design of Chemical Processes*. Technical University of Denmark, Copenhagen.

Hernjak, N., Doyle III, F.J., Ogunnaike, B.A. and Pearson, R.K. (2004). Chemical process characterization for control design. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 42–75. Elsevier, Amsterdam.

Hultgren, M., Ikonen, E. and Kovács, J. (2015). Combustion Control in Oxy-fired Circulating Fluidized Bed Combustion. In *22nd International Conference on Fluidized Bed Conversion,* Turku, Finland, Jun 14–17.

Hultgren, M., Ikonen, E. and Kovács, J. (2014). Oxidant control and air-oxy switching concepts for CFB furnace operation. *Comput. Chem. Eng.*, 61, 203–219.

Huusom, J.K. (2015). Challenges and opportunities in integration of design and control. *Comput. Chem. Eng.*, 81, 138–146.

Häggblom, K.E. (1997). Partial Relative Gain: A New Tool for Control Structure Selection. In *1997 AIChE Annual Meeting,* Los Angeles, USA, Nov 16–21.

Joronen, T., Kovács, J. and Majanne, Y. (2007). *Voimalaitosautomaatio*. Suomen Automaatioseura, Helsinki.

Kiss, A.A., Bildea, C.S. and Dimian, A.C. (2007). Design and control of recycle systems by non-linear analysis. *Comput. Chem. Eng.*, 31(5–6), 601–611.

Kookos, I.K. and Perkins, J.D. (2004). The back-off approach to simultaneous design and control. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 216–238. Elsevier, Amsterdam.

Klefenz, G. (1986). *Automatic Control of Steam Power Plants*. B.I.-Wissenschaftsverlag, Mannheim.

Lear, J.B., Barton, G.W. and Perkins, J.D. (1995). Interaction between process design and process control: the impact of disturbances and uncertainty on estimates of achievable economic performance. *J. Proc. Control*, 5(1), 49–62.

Majanne, Y. and Maasalo, M. (2009). Dynamic Simulation Assisted Design of Industrial Power Plant Process and Control. In Majanne, Y. (ed.), *6th IFAC Symposium on Power Plants and Power Systems Control,* Tampere, Finland, Jul 5–8.

Maffezzoni, C., Magnani, G.A. and Quatela, S. (1985). Process and Control Design of High-Temperature Solar Receivers: An Integrated Approach. *IEEE Trans. Autom. Control*, 30(3), 194–209.

Manousiouthakis, V., Savage, R. and Arkun, Y. (1986). Synthesis of Decentralized Process Control Structures Using the Concept of Block Relative Gain. *AIChE J.*, 32(6), 991–1003.

Meeuse, F.M. and Grievink, J. (2004). Thermodynamic controllability assessment in process synthesis. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 146–167. Elsevier, Amsterdam.

Miranda, M., Reneaume, J.M., Meyer, X., Meyer, M. and Szigeti, F. (2008). Integrating process design and control: An application of optimal control to chemical processes. *Chem. Eng. Proc. Proc. Intensif.*, 47(11), 2004–2018.

Mohideen, M.J., Perkins, J.D. and Pistikopoulos, E.N. (1997). Towards an efficient numerical procedure for mixed integer optimal control. *Comput. Chem. Eng.*, 21(Suppl.), S457–S462.

Mönnigmann, M. and Marquardt, W. (2002). Normal Vectors on Manifolds of Critical Points for Parametric Robustness of Equilibrium Solutions of ODE Systems. *J. Nonlinear Sci.*, 12(2), 85–112.

Moon, J., Kim, S. and Linninger, A.A. (2011). Integrated design and control under uncertainty: Embedded control optimization for plantwide processes. *Comput. Chem. Eng.*, 35(9), 1718–1724.

Niva, L., Ikonen, E. and Kovács, J. (2015). Self-optimizing control structure design in oxy-fuel circulating fluidized bed combustion. *Int. J. Greenh. Gas Control*, 43, 93–107.

Perkins, J.D. and Walsh, S.P.K. (1996). Optimization as a Tool for Design/Control Integration. *Comput. Chem. Eng.*, 20(4), 315–323.

Ray, T.K., Datta, A., Gupta, A. and Ganguly, R. (2010). Exergy-based performance analysis for proper O&M decisions in a steam power plant. *Energy Convers. Manag.*, 51(6), 1333–1344.

Ricardez-Sandoval, L.A., Budman, H.M. and Douglas, P.L. (2009). Integration of design and control for chemical processes: A review of the literature and some recent results. *Annu. Rev. Control*, 33(2), 158–171.

Ricardez Sandoval, L.A. (2008). *Simultaneous Design and Control of Chemical Plants: A Robust Modelling Approach*. University of Waterloo, Waterloo.

Sakizlis, V., Perkins, J.D. and Pistikopoulos, E.N. (2004). Recent advances in optimization-based simultaneous process and control design. *Comput. Chem. Eng.*, 28(10), 2069–2086.

Schweickhardt, T. and Allgöwer, F. (2004). Quantitative nonlinearity assessment – An introduction to nonlinearity measures. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 76–95. Elsevier, Amsterdam.

Schweiger, C.A. and Floudas, C.A. (1998). Interaction of Design and Control: Optimization with Dynamic Models. In Hager, W.W. and Pardalos, P.M. (ed.), *Optimal Control: Theory, Algorithms, and Applications*, 388–435. Springer, Dordrecht.

Sendin, O.H., Moles, C.G., Alonso, A.A. and Banga, J.R. (2004). Multi-objective integrated design and control using stochastic global optimization methods. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 555–581. Elsevier, Amsterdam.

Sharifzadeh, M. (2013). Integration of process design and control: A review. *Chem. Eng. Res. Des.*, 91(12), 2515–2549.

Sharifzadeh, M. and Thornhill, N.F. (2013). Integrated design and control using a dynamic inversely controlled process model. *Comput. Chem. Eng.*, 48, 121–134.

Skogestad, S. and Postlethwaite, I. (2005). *Multivariable Feedback Control, Analysis and Design*. Wiley, Chichester.

Skogestad, S. (2004) Control structure design for complete chemical plants. *Comput. Chem. Eng.*, 28(1–2), 219–234.

Swartz, C.L.E. (2004). The use of controller parametrization in the integration of design and control. In Seferlis, P. and Georgiadis, M.C. (ed.), *The Integration of Process Design and Control*, 239–263. Elsevier, Amsterdam.

Terrazas-Moreno, S., Flores-Tlacuahuac, A. and Grossmann, I.E. (2008). Simultaneous Design, Scheduling, and Optimal Control of a Methyl-Methacrylate Continuous Polymerization Reactor. *AIChE J.*, 54(12), 3160–3170.

Vega, P., Lamanna de Rocco, R., Revollar, S. and Francisco, M. (2014a). Integrated design and control of chemical processes – Part I: Revision and classification. *Comput. Chem. Eng.*, 71, 602–617.

Vega, P., Lamanna, R., Revollar, S. and Francisco, M. (2014b). Integrated design and control of chemical processes – Part II: An illustrative example. *Comput. Chem. Eng.*, 71, 618–635.

Weitz, O. and Lewin, D.R. (1996). Dynamic Controllability and Resiliency Diagnosis Using Steady State Process Flowsheet Data. *Comput. Chem. Eng.*, 20(4), 325–335.

Yuan, Z., Chen, B., Sin, G. and Gani, R. (2012). State-of-the-Art and Progress in the Optimization-based Simultaneous Design and Control for Chemical Processes. *AIChE J.*, 58(6), 1640–1659.

Åström, K.J. and Bell, R.D. (2000). Drum-boiler dynamics. *Automatica*, 36(3), 363–378.