The quest towards the integration of process control, process operations and process operability – *Industrial need or academic curiosity?*

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Historically, process control, process scheduling, and process operational functions (such as safety and maintenance) have been considered rather independently, in isolation, and/or in a sequential manner from an overall process automation perspective – primarily reflecting the widely accepted difference in their corresponding time scales (for example, days/hours for scheduling, seconds/minutes for control, etc.). However, the current trend toward real-time decision making under increasingly dynamic and volatile business, market, and supply chain environments has intensified the need for an 'integration of scales' in terms of both temporal as well as spatial considerations. The joint FOCAPO/CPC conference series over the last decade is an example of increasing evidence, at least within academic circles, of such a paradigm shift. It should not come as a surprise as there is also increasing evidence of a business driver and industrial need toward this direction.

Here, we will attempt to provide a roadmap of the evolution of the process systems engineering field toward a unification of control, operations, and operability, through industrial and research activities and developments over the last twenty years, and with the aim to elucidate the following questions:

- When does the need for such an integration of scales arise? And for what types of industrially relevant problems and application areas?
- Where do we stand regarding methodological developments and solution strategies as enablers and tools for such an integration?
- What will be an 'ideal framework' and perhaps an 'ideal software platform' for such a unification, if desired?

There has been a wealth of ongoing research in the field, as shown in Table 1, along with numerous industrial applications in the energy and other sectors, as shown in Table 2. These serve as illustrative examples of the need for and the challenges that such an integration pose. An attempt toward a grand classification of the various approaches, methods and tools is presented in Table 3. A rather personal perspective of the key drivers, gaps and opportunities will be highlighted.

List of research groups working on integration of scheduling and control

TABLE 1a	
Grossmann et al. [5 - 8]	Vassiliadis et al. [9, 10]
Maravelias et al. [11 - 14]	Dua et al. [15 - 18]
Rawlings et al. [11 - 14]	Charitopoulos et al. [15 - 18]
Ierapetritou et al. [19 - 26]	Papageorgiou et al. [15 - 18]
Baldea et al. [22, 27 - 39]	Espuña et al. [40 - 42]
Ricardez-Sandoval et al. [43 - 50]	Puigjaner et al. [40, 41]
Biegler et al. [51]	You et al. [52 - 57]
Flores-Tlacuahuac et al. [5 - 8]	Gudi et al. [58 - 60]
Zavala et al. [61]	Hedengren et al. [62 - 66]
Daoutidis et al. [1]	Marquardt et al. [67 - 70]
Swartz et al. [71]	Pistikopoulos et al. [2 - 4]

List of research groups working on integration of design with scheduling/control

TABLE 1b
Pantelides et al. [72, 73]
Daoutidis et al. [78, 79]
Douglas et al. [80, 81]
Georgiadis et al. [82 - 90]
Seferlis et al. [85]
Kwon et al. [91]
Hasan et al. [92, 93]
El-Halwagi et al. [94 - 98]
Pistikopoulos et al. [82, 86 - 88, 99 - 106]
Biegler et al. [107 - 114]
Grossmann et al. [115 - 127]
Jayaraman et al. [77]

List of research groups working on operability and safety

TABLE 1c
Pistikopoulos et al. [128 - 130, 132]
Tian et al. [128, 130, 132]
Lima et al. [131]
Douglas et al. [133]
Yang et al. [135]
Georgiadis et al. [129]
Longwell et al. [134]

TABLE 2 Industrial applications
Scheduling, optimization, and control of power for industrial cogeneration plants – Bindlish et al. [136]
Development of frameworks for integrating scheduling and control operations in manufacturing plants - Harjunkoski et al. [30]
Integration of scheduling and model predictive control in air separation unit operations - Baldea et al. [22]
Integration of planning and scheduling in hydrogen supply networks - Grossmann et al. [119]
Integration of scheduling and closed-loop control online for MMA polymer manufacturing process - You et al. [57]
Integration of scheduling and control for chemical batch processes - Wassick et al. [51]
Integration of scheduling and control for reactive distillation systems and wastewater treatment systems - Marquardt et al. [70]
Scheduling and control framework for the integration of renewable energy sources for fuel cell systems - Gudi et al. [59]
Scheduling and control of CO2 emission capture from coal-based power plant - Ricardez-Sandoval et al. [43]

TABLE 3 Grand classification of methodologies	
Author	**Contribution**
Grossman et al. [5 - 8], Flores-Tlacuahuac et al. [5 - 8], You et al. [52 - 57], Gudi et al. [58 - 60]	Simultaneous/Decomposition MIDO/MINLP open loop dynamics
Maravelias et al. [11 - 14], Rawlings et al. [11 - 14], Baldea et al. [27, 29, 38, 39], Harjunkoski et al. [38], Pistikopoulos et al. [87, 138]	Economic MPC/control theory in scheduling problems
Ierapetritou et al. [19, 25] , Marquardt et al. [67 - 70]	Simultaneous/Decomposition MIDO formulation to MINLP
Ierapetritou et al. [21, 22, 23], Baldea et al. [22], Swartz et al., Dua et al. [17, 18], Charitopoulos et al. [17, 18], Papageorgiou et al. [17, 18], Hedengren et al., Ricardez-Sandoval et al. [43, 44, 48], Pistikopoulos et al. [2, 4, 101, 103, 106]	Integration via mpMPC/NMPC/fast MPC
Ierapetritou et al. [24], Baldea et al. [28, 30, 31, 34, 35], Harjunkoski et al. [28, 30], Zavala et al. [61], Dowling et al. [61], Hedengren et al.	Data driven surrogate model and MINLP scheduling, Scale bridging control formulation in scheduling
Ierapetritou et al. [20] , Ricardez-Sandoval et al. [45, 47], Pistikopoulos et al. [102], Biegler et al. [137]	Flexibility, feasibility, scheduling under uncertainty
Ricardez-Sandoval et al. [45], Biegler et al. [51]	MIDO formulations with Stochastic back-off formulation for uncertainty
Zavala et al. [61], Dowling et al. [61]	Decomposition algorithms with surrogate model and MILP scheduling
Vassiliadis et al. [9, 10]	Multistage mixed integer optimal control formulation
Dua et al. [15], Charitopoulos et al. [15], Papageorgiou et al. [15]	multi-setpoint mpMPC scheduling layer with MILP control layer
Espuña et al. [40, 41], Puigjaner et al. [40, 41]	Simultaneous/decomposition algorithms using control/dynamics aware scheduling models
Hedengren et al. [64], Pistikopoulos et al. [3, 87]	Advanced control and MINLP scheduling schemes

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