Interaction of Design and Control

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Abstract

Traditionally, plant controllability and operability has been considered rather late in the design process, often leading to poorly performing systems. The indisputable fact that design decisions invariably impact on the controllability and resiliency of processes is driving modern design methods to handle flowsheet controllability implicitly in an integrated fashion. This paper describes the current state of the art in integration of process design and process control. A survey of the literature would suggest that two alternative approaches could be harnessed to ensure the controllability and resiliency of chemical plants. Controllability and resiliency analysis methods are used as screening methods relatively early on in the design process. Furthermore, the integrated design and control paradigms can be applied to fully optimize and integrate the design of the process and its operation. It is the objective of this presentation is to make a case for the necessary combination of these two approaches.

Keywords: Process design, Process control, Controllability and resiliency assessment, Integrated design and control.

1 Introduction

The design of a continuous chemical process has traditionally been carried out at steady state for a given operating range, it being assumed that a control system can be designed to maintain the process at the desired operating level and within the design constraints. Indeed, alternative designs are often judged on the basis of economics alone, without taking controllability and resiliency into account. This may lead to the elimination of easily controlled, but slightly less economical alternatives in favor of slightly more economical designs that may be extremely difficult to control.

Clearly unfavorable process static and dynamic characteristics could limit the effectiveness of the control system in attenuating the effect of disturbances, leading to a process that is unable to meet its design specifications. For example, a VW “Beetle” engine will not be able to perform like that of a Porsche, irrespective of the specific controller implemented. In the same way, the installation of numerous surge drums in a process adequately attenuate the effect of disturbances but possibly at the price of an unavoidable degradation of the plant’s capability to rapidly change product grades. Although the integration of design and control is universally accepted in the automotive industry, the same has not been true of the chemical industry. This is mainly due to the fact that the investment associated with refining the prototype of a car engine and its control system, which is then reproduced by the thousands, is more justifiable than that for a chemical plant, which is usually unique.

However, it is becoming increasingly evident that design on the basis of steady-state economics alone is risky because the resulting plants are often difficult to control, resulting in off-spec product,

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excessive use of fuel, and associated profitability losses. Consequently, there is a growing recognition by industrial practitioners of the need to consider the controllability and resiliency (C&R) of a chemical process during its design (Downs *et al*., 1994; van Schijndel, 1999). *Controllability* can be defined as the ease with which a continuous plant can be held at a specific steady state. An associated concept is *switchability*, which measures the ease with which the process can be moved from one desired stationary point to another. *Resiliency* measures the degree to which a processing system can meet its design objectives despite external disturbances and uncertainties in its design parameters. Clearly, it would be greatly advantageous to be able to predict how well a given flowsheet meets these dynamic performance requirements as early as possible in the design process.

Table 1 summarizes the four main stages in the design of a chemical process. In the conceptual and preliminary stages, a large number of alternative process flowsheets, in the steady state, are generated. Subsequent stages involve more detailed analysis in the steady state, followed by control system design and the verification of the dynamic performance of the controlled flowsheets. Here, considerably more engineering effort is expended than in the preliminary stages. Therefore, far fewer designs are considered, with many of the initial flowsheets having been eliminated from further consideration by screening in the preliminary stages. In this light, Perkins and Walsh (1994) report the integrated design and control of a modest wastewater neutralization system ultimately involving three unit operations. They point out that a combination of short-cut controllability assessment and steady state worst-case analysis essentially leads to the optimal design in minutes of CPU time, while dynamic optimization, requiring hours of CPU time is needed to optimize the plant's control system.

Table 1: Process Design Stages, Issues and Tools (from Seider *et al*., 1999).

Design Stage	**Issues**	**What gets fixed**	**Tools** SS C&R Dyn
1. Conceptual Design	Selecting between alternative material pathways and flowsheets.	Material pathways	
2. Development of Base-case Design	Feasibility studies based on fixed material pathways. Unit operations selection. Heat integration superstructure.	Flowsheet structure	
3. Detailed Design.	Process variable optimization. Sensitivity analysis to process disturbances and uncertainties.	Optimal flowsheet parameters	
4. Plant-wide Controllability Assessment.	Flowsheet controllability. Dynamic response of the process to disturbances. Selection of the control system structure and its parameters.	Control structure	

Clearly, it is desirable to ensure that the flowsheet being designed can be operated is such a way as to meet its objectives despite external disturbances and possible uncertainties associated with the design. The designers must choose between a number of alternatives:

1. Design first, then worry about control. This assumes that steady state economics dominates the design problem, and that any disturbances/perturbations in externally defined process variables can be completely handled by appropriate control action. This assumes (a) perfect control action is possible and (b) the absence of physical limits to control action (neither static nor dynamic). This approach has the advantage of being simple to implement, and would permit the design to be effected using only steady-state flowsheeting software. It is also quite close to the current industrial practice. However, its main disadvantage is that the procedure may lead to uncontrol-

lable designs at worst, or to designs with poor resiliency at best. Furthermore, the consequences cannot be predicted in advance so the designer may be in for unpleasant surprises.

2. Do the design first, but at least screen alternative designs for controllability as you go along. Only those designs that can guarantee minimal control performance should be developed further, with those that fail to meet the minimum specifications eliminated. The advantages of this approach are its relative simplicity, given its reliance only on steady state flowsheet information. Thus, it can be integrated into standard practice and can be implemented on large-scale systems. The reliance on C&R measures, which do not require a priori control system design, also means that dynamic simulation is not required at this stage, which is another important advantage. On the downside, it may be difficult to interpret the results based on linear approximations, which are prone to be sensitive to the uncertainties associated with linearization. Thus, if used, this approach must include the impact of uncertainty to ensure its reliability. Alternatively, nonlinear analysis can be invoked. Both approaches rely on mature linear and nonlinear analysis and to specific results related to flowsheet controllability, which will be discussed in **Section 2** of this paper.
3. Carry out integrated design and control. This mathematically attractive approach considers process design and process control simultaneously as one integrated optimization problem. The obvious advantage is that the complete process in all its intricacies can be considered in a detailed mathematical formulation of the problem, which releases the designer from a dependency on rather less reliable linear approximations required to implement the linear controllability analysis. On the other hand, this is attained at the cost of more effort required to develop the more detailed models that are required. Consequently, for a tractable solution, this often requires the adoption of simplifying assumptions, or will limit the approach to small-scale problems. Furthermore, the integrated approach will require the additional burden of designing and implementing a control system, which will bias the results of the analysis with regards to the particular control design approach taken. Finally, mathematically attractive performance objectives, such as the ISE of the tracking error that could be adopted in an overall objective function, may not make sense practically. This approach will be discussed in some detail in **Section 3** of this paper.

The second and third alternative paradigms have and will continue to change the way that modern process design is carried out. One of the objectives of this paper is to show that the two approaches are in fact complimentary. The need to account for the controllability of competing flowsheets in the early design stages is an indication that simple screening measures, requiring the limited information available, should be used to select from amongst the flowsheets. Here, if high fidelity, closed-loop, dynamic modeling were used, the engineering effort and time required for development and analysis would *slow* the design process significantly. The right-hand-side columns in Table 1 show that the short-cut C&R tools provide a bridge between steady-state simulation for process design and the rigorous dynamic simulation required to verify switchability and other attributes of the closed-loop dynamics of the final design.

This paper is structured as follows. First, in **Section 2**, the major research results on which the linear and nonlinear controllability analysis is based will be described, as well as their impact on design. In **Section 3**, an overview is presented on the integrated design and control paradigm. Finally, the possible combination of the two approaches is discussed, as well recommendations for engineering education.

2 The Role of Controllability Analysis

2.1 Linear Controllability Assessment.

With the maturity of linear controllability and resiliency analysis, largely in the 80's (e.g., Morari, 1983; Perkins, 1989), several tools and concepts have emerged, relying on linear transfer function matrices, $\underline{\boldsymbol{P}}(s)$ and $\underline{\boldsymbol{P}}_d(s)$, which relate the effect of manipulated variables, $\underline{\boldsymbol{u}}(s)$, and disturbances, $\underline{\boldsymbol{d}}(s)$, on the process outputs, $\underline{\boldsymbol{y}}(s)$:

$$\underline{\boldsymbol{y}}(s) = \underline{\boldsymbol{P}}(s)\,\underline{\boldsymbol{u}}(s) + \underline{\boldsymbol{P}}_d(s)\,\underline{\boldsymbol{d}}(s)$$

The most important of these are:

Relative gain array (RGA). The coefficients of the RGA are ratios of the process gain as seen by a given SISO input-output combination with all other control loops in manual, with the same gain with all other loops perfectly controlled. It has important ramifications on the selection of plant-wide control loop configuration (Bristol, 1966; McAvoy, 1983) as well as on the sensitivity of the attainable closed-loop performance to uncertainties in $\underline{\boldsymbol{P}}(s)$ (Grosdidier *et al.*, 1985, Morari and Zafiriou, 1989; Hovd and Skogestad, 1992).

Singular value decomposition (SVD). The matrix $\underline{\boldsymbol{P}}(s)$is transformed by SVD into the product of two rotational matrices and a diagonal matrix of singular values. The minimum and maximum singular values (σ_{min} and σ_{max}, respectively) both provide information regarding the impact of manipulated variable constraints on the controllability of the process. The condition number of the process, which is the ratio, $\sigma_{max}/\sigma_{min}$, provides an indication of process ill conditioning, that is, processes in which the process output amplitudes will be strongly dependent on the input direction. Such processes are expected to be significantly more difficult to control (Morari and Zafiriou, 1989).

Performance limits associated with non-minimum-phase (NMP) components. It is important to understanding the unavoidable limits to closed loop performance of inverse-response phenomena associated with right-half-plane zeros and of delays in $\underline{\boldsymbol{P}}(s)$ as unavoidable limits to closed loop performance (Holt and Morari, 1985a and 1985b). These results have been recently extended to handle unstable systems (Havre and Skogestad, 1998).

Quantifying the impact of disturbances on achievable performance. Various measures have been suggested in the literature to quantifying the effect of disturbances on achievable performance:

- RDGA – Relative disturbance gain array (Stanley *et al*., 1985)
- DCN – Disturbance condition number (Skogestad and Morari, 1987)
- DC – Disturbance cost (Lewin, 1996)
- IDA – Input disturbance alignment (Cao and Rossiter, 1998).

All of these measures rely on the availability of the matrices $\underline{\boldsymbol{P}}(s)$ and $\underline{\boldsymbol{P}}_d(s)$, and are based on perfect control. As such, they provide diagnosis tools that can eliminate a flowsheet that is unable to achieve the desired specification even in a perfect control setting. Apart from the DC, which can handle multiple disturbances, the other measures allow only for the analysis of single disturbances. Furthermore, the RDGA and IDA are limited to steady state analysis.

Quantifying the effect of recycles on achievable performance. It is well known that energy recycling, associated with heat integrated systems, such as heat exchanger networks and autothermal reactors, contributes positive feedback to the system, which is potentially destabilizing. Denn and Lavie (1982) were the first to show that material recycle increases the overall response time of the process, as well as increasing its static gain. Luyben (1993) coined the term "snowball effect", which describes the phenomena associated with the inability of a control structure to attenuate the effect of a disturbance on the output variables associated with material recycle. Several approaches have been used to quantify the problem (e.g., Semino and Giuliani, 1997; Jacobsen, 1997; Dimian *et al*., 1997); McAvoy and Miller, 1999).

These tools depend on the availability of adequate linear approximations for the process dynamics. Short-cut methods that enable approximate process dynamics to be estimated using steady state flowsheet data have been presented by Weitz and Lewin (1996) and Seider *at al*. (1999). The overall C&R diagnosis therefore consists of a method for the generation of approximate linear process dynamics, in combination with the linear diagnosis tools mentioned above. This has been shown effective in correctly screening for adequate controllability and resiliency for a large number of processes. This session includes two examples of applications of C&R diagnosis: Andersen *et al.* (1999) present the incorporation of linear and nonlinear C&R analysis within flowsheeting software, and Solovyev and Lewin (1999) present an example of the application of linear C&R analysis on a heat-integrated distillation column.

2.2 Control Structure Selection.

The importance of controllability measures (e.g., RGA and SVD) and disturbance impact measures (e.g., RDGA, DCN and DC) for the selection of appropriate control structures has been established by the numerous studies in their application reported in the literature. Seferlis and Grievink (1999) present a screening method for control configurations that identify potential static manipulated variable constraints to achieving process specification in the presence of multiple disturbances. Kookos and Arvanitis (1999) present a method for automatic control-system configuration in this session.

A relatively novel concept is that of the *partial control* in multivariable systems. Usually, the number of manipulated variables is far less than the number on outputs to control, indicating that only a subset of the outputs can be guaranteed to meet their specification with no offset. In *partial control*, this subset is selected in such a way as to guarantee that the entire output set can be guaranteed to converge to a prespecified hyperspace. Arbel *et al*. (1996) illustrate this concept in an application involving the control of an FCC, in which they also indicate the importance of nonlinear analysis.

2.3 Nonlinear Analysis.

Clearly, the reliability of a linear approximation of the process model may be compromised, especially for processes that feature severe nonlinearities. Despite this limitation, linear analysis has had an excellent track record in the diagnosis of process flowsheet controllability analysis. However, for highly nonlinear systems that feature multiplicity phenomena, nonlinear analysis is crucial in realizing the full potential in design. A comprehensive review of nonlinear analysis is offered by Seider *et al*. (1991). More specifically, Seider *et al*. (1990) provide many examples in process design where it may be advantageous to select non-conventional and more problematic operating regimes to enhance the plant's profitability. Seider (1999) extends these ideas in this session, in which the case is presented for reactor design and operation at open-loop unstable conditions.

The need for nonlinear analysis in process controllability is also clear. In this light, Vinson and Georgakis (1998) proposed a nonlinear controllability measure based on the computation of proportion of the desired operating range that can be attained by the available input space. Uzturk and Georgakis (1998) extended this approach for SISO systems to consider also simple process dynamics based on constrained optimization. The economic cost of backing off from constraints to ensure that a process can satisfy its specifications in the event of bounded disturbances is quantified by Bandoni *et al*. (1994); this approach allows the justification of adopting appropriate feedback control, in the light of the otherwise incurred open-loop backoff cost. This approach is extended to include also dynamic analysis by Figueroa *et al*. (1994).

3 The Role of Integrated Design and Control

Clearly, the design of a process should consider its operability and controllability. Brengel and Seider (1992) consider the tasks of detailed process design and control system design together. Their approach provides optimal vessel sizing and nominal operating point definition as well as the simultaneous development of a non-linear MPC controller. Their approach only considers the design of single unit operations, and therefore does not treat the combinatorial issues associated with alternative process configurations.

Luyben and Floudas (1994), Bansal *et al*. (1998) and Ross *et al*. (1999) consider the optimal design of heat integrated distillation columns using a MINLP (Mixed Integer Non-linear Program) optimization approach. In all three contributions, the alternative heat-integrated configurations of two columns are presented to the MINLP solver as a superstructure, together with a detailed model of the process, and a representation of the control objectives. The approaches differ mainly in the way that the control objectives are defined. Luyben and Floudas (1994) propose the use of a multiobjective approach in which the solutions are parameterized as a function of the process condition number, but report the severe non-convexities associated with their approach. The cost decreases sharply as the process design is switched from a single- to a double-effect configuration, at the cost of increased condition number. Their conclusions are to select the double-effect configuration with the smallest condition number, but note the sensitivity of their results to the selection of the trade-off weights. In contrast, Bansal *et al*. (1998) and Ross *et al*. (1999) include the closed-loop performance under PI multivariable control as part of the design objectives. To enhance the convexity of their objective function, the performance is expressed as the ISE (integral square error) of the process outputs. The main problem with this approach is that the results may not be particularly relevant with regards to control performance, biased with regards to the particular controller structure and tuning selected, and again, sensitive to the trade-off weights selected.

Thus far, the types of problems approached using MINLP have been limited to rather simple problems involving a small number of unit operations. The reason for this is the combinatorial explosion of alternatives that have to be considered in the superstructure. Intelligent pruning of the superstructure that is presented to the MINLP is required to generate a tractable problem.

4 The Future

This paper may be summarized by focussing on three critical aspects that will characterize future activity in integrated design and control:

1. The quantitative assessment of chemical process controllability and resiliency (C&R) has generated considerable interest, both academically and in industry. The vendors of commercial flowsheeting software equate controllability assessment with dynamic simulation, and ultimately, plant-wide operability and controllability needs to be verified using this important tool. However, it is actually more important to be able initiate C&R diagnosis without requiring this expensive and engineering-intensive activity. It has been shown that the early-stage controllability analysis is important way to reduce the alternatives at an early stage of the design. The challenge to the software vendors is to build these tools directly into flowsheeting software.
2. Without a doubt, integrated design and control is an important way to polish a final design. To effectively use the MINLP approaches under development to the design of real processes, it is necessary to develop appropriate methods to compact the superstructure presented to the MINLP solver, to enable the tractable solution of large-scale problems. Currently, such problems are only solvable by heuristics. Clearly, the inclusion of C&R analysis within a MINLP approach could provide this missing link.

3. The appropriate training of chemical engineers, who should be taught to see the design and control of chemical processes as an integrated activity, is a precondition to the future advance of this field (Seider at al., 1999). To this end, both the fundamentals of process dynamics and control, and the impact of design on control, have to be adequately covered in the scope of undergraduate level education.

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