Computers and Chemical Engineering 70 (2014) 22–34

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Evolution of concepts and models for quantifying resiliency and flexibility of chemical processes

Ignacio E. Grossmann*, Bruno A. Calfa, Pablo Garcia-Herreros

Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15123, United States

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form
21 December 2013
Accepted 26 December 2013
Available online 8 January 2014

Dedicated to Manfred Morari for his pioneering and inspiring research work that has produced major advances in process systems engineering.

Keywords:
Flexibility
Resiliency
Design under uncertainty
Dynamic resiliency

ABSTRACT

This paper provides a historical perspective and an overview of the pioneering work that Manfred Morari developed in the area of resiliency for chemical processes. Motivated by unique counter-intuitive examples, we present a review of the early mathematical formulations and solution methods developed by Grossmann and co-workers for quantifying Static Resiliency (Flexibility). We also give a brief overview of some of the seminal ideas by Manfred Morari and co-workers in the area of Dynamic Resiliency. Finally, we provide a review of some of the recent developments that have taken place since that early work.

1. Introduction

This paper is a tribute to the pioneering work by Manfred Morari in the area of resiliency that he initiated during his early years at the University of Wisconsin (1977–1983) and later was a major part of his research at Caltech (1983–1994).

We first give an account of the early relation that Ignacio Grossmann was fortunate to establish with Manfred Morari through their discussions on Flexibility and Resiliency, which are major components of the operability of chemical processes. We then provide two motivating examples that show the non-trivial nature of these areas, and which motivated much of the subsequent research. We next give a brief review of the early mathematical formulations and solution methods developed by Grossmann and co-workers for addressing these problems, which can also be found in Biegler, Grossmann, and Westerberg (1997). We also briefly review the major contribution by Morari and co-workers. Finally, we close with the new developments and extensions that have taken place since that early work.

2. The early years of flexibility and resiliency

Ignacio Grossmann met Manfred Morari in 1980 on their way to Hennicker to attend the 1st FOCAPD meeting organized by the late Dick Mah and Warren Seider. At the time Ignacio asked Manfred: what are you working on these days? He replied: on Resiliency. What about you? Ignacio replied: I am working on Flexibility. They both thought: Flexibility or Resiliency?

According to Merriam Webster, Flexibility is the ready capability to adapt to new, different, or changing requirements, while Resiliency is the capability to recover or adjust easily to misfortune or change. Clearly not much of a difference, except that Flexibility might be better suited for optimists, while Resiliency might be better for pessimists!

After this encounter, Manfred and Ignacio joined forces at the 2nd FOCAPD meeting that took place at Snowmass, and was organized by Art Westerberg and Henry Chien. That led to their joint paper (Grossmann & Morari, 1984) in which for the first time they quantitatively articulated the properties of Flexibility and Resiliency, with the former generally addressing the capability of feasible operation in the steady state, and the latter addressing the dynamic capability to easily recover from process disturbances in a fast and smooth manner.

More specifically, the motivation of this early work was to incorporate operability considerations at the design stage. The

* Corresponding author. Tel.: +1 412 268 3642; fax: +1 412 268 7139.
E-mail address: grossmann@cmu.edu (I.E. Grossmann).

0098-1354/$ – see front matter
http://dx.doi.org/10.1016/j.compchemeng.2013.12.013

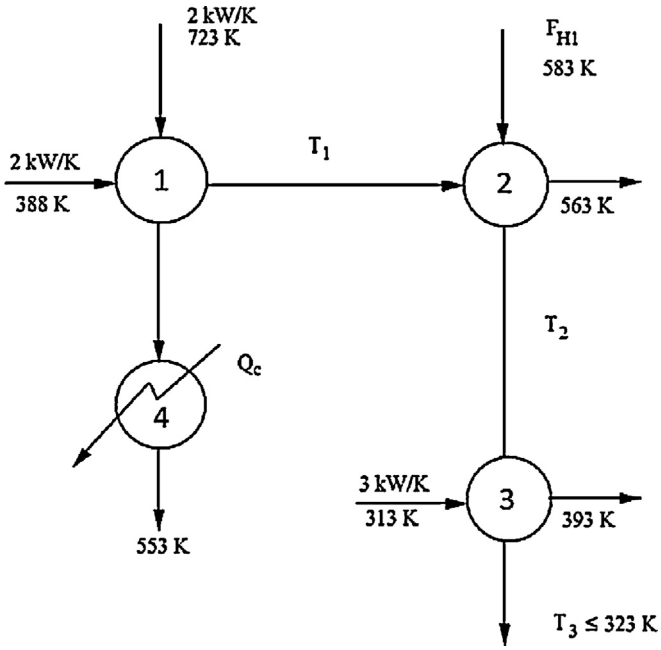

Fig. 1. Heat exchanger network with uncertain heat capacity flowrate, F_{H1}.

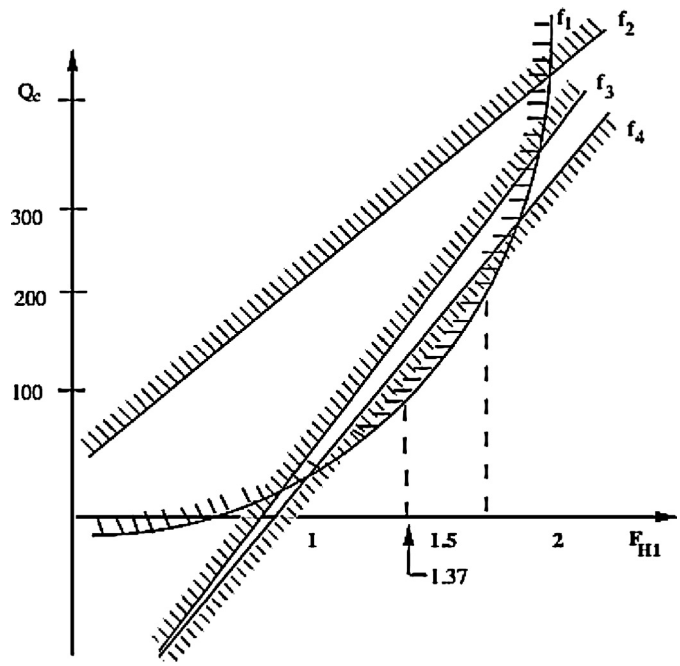

Fig. 2. Feasible region for constraints in (2).

conventional approach is to consider only nominal conditions without anticipating effects of changes and uncertainties in plant operation. The remedy is to use overdesign to compensate for lack of anticipation. In contrast, steady-state Flexibility or Resiliency addresses the guaranteed feasibility of operation of a plant over a range of conditions, with the ultimate goal being on how to design a process for guaranteed flexible/resilient operation. Furthermore, dynamic Resiliency is concerned with fast and smooth changeover and recovery from process disturbance, with the ultimate goal of determining the inherent dynamic characteristic of a plant *independent* of the selection of a particular controller. To appreciate why these are non-trivial problems we review two motivating examples in the next section.

3. Motivating examples

Let us consider the heat exchanger network shown in Fig. 1 (Biegler et al., 1997), a slight modification of the pioneering example by Saboo and Morari (1984) in which the heat capacity flowrate F_{H1} is an uncertain parameter. We would like to determine whether this network is feasible for the range $1 \le F_{H1} \le 1.8$ (kW/K).

The following inequalities are considered for feasible operation of this network:

$$\begin{aligned} &\text{Feasibility in exchanger 2}: && T_2 - T_1 \ge 0 \\ &\text{Feasibility in exchanger 3}: && T_2 - 393 \ge 0 \\ &\text{Feasibility in exchanger 3}: && T_3 - 313 \ge 0 \\ &\text{Specification in outlet temperature}: && T_3 \le 323 \end{aligned} \qquad (1)$$

By considering the corresponding heat balances, we can solve for the above temperatures in terms of the cooling load Q_c, that can be regarded as a control variable (i.e. degree of freedom), and in terms of F_{H1}, the uncertain parameter. The reduced inequalities in (1) are then as follows:

$$\begin{aligned} f_1 &= -25 + Q_c\left[\frac{1}{F_{H1}} - 0.5\right] + \frac{10}{F_{H1}} \le 0 \\ f_2 &= -190 + \frac{10}{F_{H1}} + \frac{Q_c}{F_{H1}} \le 0 \\ f_3 &= -270 + \frac{250}{F_{H1}} + \frac{Q_c}{F_{H1}} \le 0 \\ f_4 &= 260 - \frac{250}{F_{H1}} - \frac{Q_c}{F_{H1}} \le 0 \end{aligned} \qquad (2)$$

Plotting the inequalities in (2) in terms of Q_c, the control variable, and in terms of F_{H1}, the uncertain parameter, we can see that the inequalities are satisfied at the extreme points $F_{H1} = 1$ kW/K, say for $Q_c = 15$ kW, and at $F_{H1} = 1.8$ kW/K, say for $Q_c = 227$ kW. That is, by adjusting the cooling load one can achieve feasibility of operation in the network at the extreme points. If we did not plot the feasible region we may be tempted to conclude that the network is feasible to operate for the range $1 \le F_{H1} \le 1.8$ kW/K. However, from Fig. 2, we can see that for an intermediate value, like $F_{H1} = 1.2$ kW/K, the inequalities define an empty feasible space even if we set the cooling load to say $Q_c = 58.6$ kW. In other words the network is infeasible at the *non-vertex* point $F_{H1} = 1.2$ kW/K. Furthermore, from Fig. 2 we can clearly see that we have a non-convex region where for $1.118 \le F_{H1} \le 1.65$ we have infeasible operation. In fact at $F_{H1} = 1.37$ kW/K we have the greatest violation of constraints. Hence, $F_{H1} = 1.37$ kW/K corresponds to the critical point. This brilliant example by Saboo and Morari (1984) shows that it is possible to have non-vertex critical points, and consequently, that we need appropriate methods that will be able to predict such points.

The next motivating example (Grossmann & Morari, 1984) shows that the sensitivity of a multivariable control system to plant parameter variations is not only a function of the control system design, but even more so of the system itself. Fig. 3 shows a system of thermally coupled distillation columns, which is used to separate a 70% methanol/water mixture into a 99% methanol distillate and a 0.1% methanol bottom product (more details on the model and analyses can be found in Lennhoff & Morari, 1982).