

# Design for Flexibility: A Robust Optimization Approach

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Flexibility is a critical feature of any industrial system as it tells us about the range of conditions under which the system can effectively and safely operate. It is becoming increasingly important as we face greater volatilities in market conditions, diverse customer needs, more stringent safety and environmental regulations, the growing use of resources with varying availability such as renewable energy, and an increased likelihood of disruptions caused by, for example, extreme weather.

In process systems engineering, there is a long history of applying *flexibility analysis* [1] to evaluate and design flexible process systems. In particular, Swaney and Grossmann [2] introduced the concept of flexibility index to quantify the level of operational flexibility in a given design. Here, one assumes that the system's input parameters can take values within certain ranges defined by a so-called uncertainty set, which typically takes the form of a hyperrectangle. The size of the uncertainty set is given by a scalar parameter, and for a given design, the flexibility index is the largest possible value of that size parameter for which the operation of the system is guaranteed to be feasible with proper adjustment of the control variables. In addition, we often want to optimize the design of a system while satisfying given flexibility requirements. In that case, the uncertainty set is fixed, and the design problem can be formulated as a two-stage robust optimization problem [3].

In this work, we propose a new design approach that can directly determine the design that maximizes the flexibility of the system. It also provides a rigorous way of investigating the trade-off between cost and flexibility, and it can be especially useful when the uncertainty set has a more complex structure with multiple parameters defining its shape and size. We find that the problem can be formulated as a two-stage robust optimization problem with endogenous uncertainty [4]. Its trilevel nature and the decision-dependent uncertainty set give rise to a computationally highly complex optimization problem. For its solution, we apply variants of the column-and-

constraint generation algorithm proposed by Zeng and Wang [5]. We demonstrate the key features and efficacy of this new design approach using several examples, including a computational case study considering the design of a supply chain involving mobile modular plants under uncertainty.

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