Process Flexibility for Multi-Period Production Systems

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Introduction. In today’s market, firms are often required to offer their customers more diverse product portfolios in order to keep ahead of the market competition. The increase in product offerings, however, would invariably drive up the variabilities of product demands. To deal with this challenge, it has been observed that firms often adopt an operational strategy known as process flexibility (see Simchi-Levi (2010) and Cachon and Terwiesch (2009)). Also known as capacity pooling, process flexibility allows the firm to quickly change the production of different types of products from one plant to another with little penalty in time and cost, thereby adapting itself to reduce the operational costs under demand fluctuations.

Firms can choose to add different degrees of process flexibilities to their production system. For example, a production system has full flexibility if any of its plants is capable of producing any of the product (see Figure 1). While a fully flexible system has important benefits such as capacity pooling, it is often impractical due to its enormous implementation cost. As a result, many manufacturers have chosen to add a sparse amount of process flexibility, where each plant is only capable of producing a small subset of the products. Surprisingly, researchers have observed that this practice is often enough to guarantee excellent or even near-optimal performance. In the seminal paper of Jordan and Graves (1995), the authors observed that by adding a little bit of flexibility to the plants to create a chaining structure (also referred to as the long chain, illustrated in Figure 1), one often obtains almost the same benefit as a fully flexible system.

Much of the theoretical analysis on this topic focuses on a single-period model (see, e.g., Chou et al. (2010, 2011), Simchi-Levi and Wei (2012), Wang...
Figure 1: Examples of Process Flexibility Structures.

and Zhang (2015), Chen et al. (2015), Désir et al. (2016)). However, in practice, firms often operate in a multi-period setting, where the unsatisfied demand is backlogged into future time periods. The multi-period setting gives rise to a complex multi-stage closed-loop dynamic optimization problem, where the analysis of the single-period model does not carry through. This naturally leads to the following research question: In a multi-period make-to-order environment, can a sparse flexibility structure achieve a performance that is close to that of the full flexibility structure?

Our Contributions. In this paper, we provide an affirmative answer to the question above. The first major contribution of our paper proves that under realistic modeling assumptions, for any system with $m$ plants and $n$ products, there exists a sparse structure with only $m + n$ flexibility arcs, such that the sparse structure achieves approximately the same performance as full flexibility structure (consisted of $mn$ arcs) as the plants becomes heavily utilized. In addition, the proof of our result is constructive, thereby providing an efficient algorithm for designing near-optimal, sparse flexibility structures.

Another major contribution of the paper is that we establish the necessity of having at least $m+n$ arcs for a flexibility structure to achieve a performance that is close to that of full flexibility. More specifically, we construct example systems in which any flexibility structure with at most $m+n-1$ arcs has a performance that is at least a constant factor away from the performance of full flexibility. As
a result, our analysis not only echoes “a little bit of flexibility goes a long way”, a recurrent theme in the process flexibility literature, but also quantifies exactly how much flexibility is needed in the multi-period make-to-order environment. Moreover, an important step in characterizing the performance of these systems uses a lower bound on the performance of any flexibility structure, which we believe is of independent interest.

References