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Flexibility analysis of process supply chain networks

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ABSTRACT

One of the key fundamentals for organizations to remain competitive in the present economic climate is to effectively manage their supply chains under uncertainty. The notion of supply chain flexibility attempts to characterize the ability of a supply chain to perform satisfactorily in the face of uncertainty. However, limited quantitative analysis is available. In this work, we utilize a flexibility analysis framework developed within the context of process operations and design to characterize supply chain flexibility. This framework also provides a quantitative mapping to various types of flexibility discussed in the operations research and management science literature. Two case studies are included to illustrate the application of this framework for analyzing the flexibility of existing supply chain processes, as well as utilizing it in supply chain design.

1. Introduction

A supply chain is defined in Simchi-Levi et al. (2003) as a network within an organization or between multiple organizations that involves the procurement of raw materials, conversion from raw materials to final products, and distribution of final products to markets. A supply chain involves the flow of products, finances and information. A key feature for businesses nowadays is that it is the entire supply chain that competes, not solely individual organizations, and the success of supply chains is ultimately determined by the end consumers (Christopher, 2005). Trends of increased market competition, rising costs, and increased globalization of manufacturing, supply and distribution, all contribute to the ever increasing importance of effective supply chain management to reduce costs, maintain acceptable service levels and mitigate uncertainty. This motivates the development of quantitative and systematic approaches for supply chain operation and design, and that recognize the supply chain as integrated system of components and decision levels (Grossmann, 2005; Papageorgiou, 2009).

Processes and supply chains operate in an environment of uncertainty, and in order to remain competitive, must have a requisite level of robustness to changing conditions – both exogenous and endogenous. Sources of uncertainty include variation in demand (which is commonly encountered, particularly with increasing trends toward the manufacture of high value specialty products), supply, costs, and manufacturing equipment degradation and failure. Key properties that reflect this capacity to mitigate uncertainty are flexibility and responsiveness, which are now considered as a strategic capability (Stevenson and Spring, 2007). While manufacturing flexibility has been the subject of numerous publications, supply chain flexibility has been only relatively recently been addressed, with limited quantitative analysis.

Uncertainty in process plant conditions has led to the development by Grossmann and coworkers of a quantitative framework for process flexibility analysis (Halemane and Grossmann, 1983; Swaney and Grossmann, 1985). Within this paradigm, flexibility is defined as the ability to maintain feasible steady-state operation for all parameter values within a specified range. In Swaney and Grossmann (1985), a flexibility index is defined that represents the largest scaled parameter range for which feasible operation can be maintained. Overviews of this framework, as well as extensions and applications, are given in Grossmann and Morari (1984), Biegler et al. (1997) and Grossmann et al. (2014).

This paper presents an optimization-based flexibility analysis framework for supply chain networks inspired by the process systems engineering methodology. The flexibility analysis provides a quantitative characterization on how flexible a supply chain process is, and also delivers a mapping to different types of flexibility discussed in operations research and management science literature. The proposed approach can be applied to existing supply chains for performance assessment based on economic and flexibility criteria, and can also be used within a supply chain design

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setting. The methodology outlined is not limited to a specific supply chain configuration, and is applicable to a wide range of industrial sectors.

The remainder of this paper is organized as follows. Section 2 provides an overview of supply chain flexibility analysis definitions, concepts and approaches. Section 3 provides an overview of the flexibility analysis framework developed for process plant systems, upon which the proposed framework draws. Section 4 details the development of the flexibility analysis framework for process supply chains, including the mathematical model of a representative supply chain system and the optimization formulation for flexibility analysis. In Section 5, illustrative case studies are presented to demonstrate the application of proposed framework for evaluating the flexibility of a process supply chain, as well the utilization of this framework in a design setting. Finally, concluding remarks are made in Section 6.

2. Supply chain flexibility

This section provides an overview of several approaches toward supply chain flexibility analysis. We begin with a brief discussion on manufacturing flexibility, which predates supply chain flexibility and from which many concepts on supply chain flexibility are drawn.

The seminal contributions in manufacturing flexibility by Slack (1987) and Upton (1994) pose types and dimensions of flexibility in manufacturing systems. Slack (1987) identifies four types of flexibility (product, mix, volume, delivery), and two dimensions of flexibility: range and response. Range refers to the range of states that can be achieved by the production system or resource, while response refers to the cost and time associated with transitioning between states. Building on the framework of Slack (1987), Upton (1994) identifies uniformity as the third dimension of the flexibility, which refers to the ability of delivering consistent performance throughout a range. The author further distinguishes between external and internal flexibility. External flexibility is viewed as a source of competitive advantage, and the internal flexibility is the internal capability by which external flexibility can be achieved. Sethi and Sethi (1990), in a comprehensive review on manufacturing flexibility, describe flexibility as a complex, multidimensional concept that is hard to capture, and refer to the fact that at least 50 different terms for various types of flexibility have appeared in the manufacturing literature. An overview by Kaighobadi and Venkatesh (1994) reviews the literature on the definitions of flexible manufacturing system (FMS), the classification of FMSs, and the installation and implementation issues of FMSs. FMSs can be classified into dedicated, sequential and manufacturing cells based on the level of flexibility, average lot size, and number of parts in product family. De Toni and Tonchia (1998) also analyze the literature on manufacturing flexibility through consideration of six different aspects of flexibility: definition, request, classification, measurement, choice and interpretation. In addition, the authors refer to Mandelbaum (1978)'s distinction between state flexibility and action flexibility, with state flexibility referring to the ability to work despite changes in the environment, and action flexibility being the ability to react to the changes, and in particular to transition from one operational state to another.

Vickery et al. (1999) define five types of supply chain flexibility (product, volume, new product, distribution and responsiveness), with most of these types of flexibility covering the responsibilities of a particular area or function of the organization. Duclos et al. (2003) point out the lack of the cross-functional perspectives of supply chain flexibility and that the concept of flexibility should be extended to the entire supply chain. The authors then identify six aspects of supply chain flexibility, recognizing the requirement of flexibility within and between the functional components of the chain, as well as the flexibility to gather and exchange information between organizations. Sánchez and Pérez (2005) explore the relationship between the dimensions of supply chain flexibility and the performance of organizations using multivariate analysis of data obtained through a survey. Kumar et al. (2006) develop a conceptual approach to implement and manage supply chain flexibility. The proposed framework features a three-stage process: identify required flexibility, implement and share responsibility, and then feedback and control to sustain. A comprehensive review by Stevenson and Spring (2007) provides a more complete definition of supply chain flexibility, and identifies gaps in the literature including a limited focus of the analysis on a plant or firm, and failure to explore the full impacts of supply chain flexibility between multiple organizations. Yi et al. (2011) conduct a study involving five companies, and define four flexibility strategies in operations management (conservative, agile, aggressive and laggard), based on the supply chain flexibility relative to the supply chain uncertainty.

Most of above discussions on manufacturing and supply chain flexibility are conceptual and qualitative in nature. However, a number of contributions featuring analytical methodologies have been proposed. Son and Park (1987) define and quantify four types of partial flexibility measures (equipment, product, process, and demand) and a total flexibility measure to integrate the partial measures. Beamon (1999) identifies flexibility as one of three key types of supply chain performance measures, and proposes metrics for the evaluation of four types of flexibility (volume, delivery, mix, and new product flexibility). Garavelli (2003) takes into account two aspects when addressing supply chain flexibility: process flexibility, and logistics flexibility. Process flexibility refers to the number of products that can be manufactured at each production site, while logistics flexibility indicates different logistics strategies that can be adopted. The author examines the impact of process flexibility and logistics flexibility on supply chain performance through a simulation model, utilizing work-in-progress and lead time as performance measures. Aprile et al. (2005) adopt a similar approach, but assess the impact of flexibility on lost sales. Both studies try to guide the selection of suitable level of flexibility based on different supply chain configurations, and evaluating the impact of limited versus total flexibility. Barad and Even Sapir (2003) propose a framework for flexibility in logistic systems, and present a quantitative analysis of trans-routing flexibility through a multi-factor design of experiments approach. Based on dimensions of flexibility proposed by Slack (1987), Barad and Even Sapir (2003) also suggest measuring trans-routing flexibility on a response dimension as the time or cost necessary to transfer stock from one location to another at the same echelon. On a range dimension, the number of transshipment links per location is used as a quantitative measurement. Gong (2008) proposes a supply chain flexibility model comprising labor flexibility, routing flexibility, machine flexibility, and information technology. The total system flexibility is measured by a profit index, and can also assist in making supply chain flexibility-promotion decisions. Tang and Tomlin (2008) discuss flexibility strategies for reducing the impact of several supply chain risks they identify. They also provide quantitative analysis under simplifying assumptions in order to develop relationships between the level of flexibility and its mitigating effects. The strategies addressed include multiple suppliers, flexible supply contracts, flexible manufacturing processes, flexibility via postponement, and flexibility via responsive pricing.

Mansoornejad et al. (2010) propose a hierarchial approach to integrate product portfolio selection with supply chain analysis. The approach includes consideration of manufacturing flexibility through the configuration of product lines. Mansoornejad et al. (2011) identify four major types of flexibility studied within the chemical engineering literature as recipe, product, volume and