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Frontier-based performance analysis models for supply chain management: State of the art and research directions

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ABSTRACT

Effective supply chain management relies on information integration and implementation of best practice techniques across the chain. Supply chains are examples of complex multi-stage systems with temporal and causal interrelations, operating multi-input and multi-output production and services under utilization of fixed and variable resources. Acknowledging the lack of system's view, the need to identify system-wide and individual effects as well as incorporating a coherent set of performance metrics, the recent literature reports on an increasing, but yet limited, number of applications of frontier analysis models (e.g. DEA) for the performance assessment of supply chains or networks. The relevant models in this respect are multi-stage models with various assumptions on the intermediate outputs and inputs, enabling the derivation of metrics for technical and cost efficiencies for the system as well as the autonomous links. This paper reviews the state of the art in network DEA modeling, in particular two-stage models, along with a critical review of the advanced applications that are reported in terms of the consistency of the underlying assumptions and the results derived. Consolidating current work in this range using the unified notations and comparison of the properties of the presented models, the paper is closed with recommendations for future research in terms of both theory and application.

1. Introduction

Supply chain management (SCM) was introduced as a common scientific and managerial term in 1982 (cf. Oliver & Webber, 1992) to describe a hierarchical control system for material, information and financial flows in a potentially multidirectional network of autonomous decision making entities. Although there is a lack of universally accepted definition (Otto & Kotzab, 1999), a well-used and typical definition of a supply chain is '*a network of organizations that are involved, through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hand of the ultimate consumer*' Christopher (1998, p. 15). The management activity is consequently the coordination of this network, or 'chain', of independent processes as to achieve the overall goal in terms of value creation. Three elements are important in our context: the *multi-level character* of the network, the *interdependency* and the *competitive* objective. First, the underlying system is constituted of multiple layers, both horizontally (sequential processing) and vertically (control layers, levels of integration into firms, business units, joint ventures, information sharing, etc.). This implies that the systematic analysis of a supply chain must take into account the level of processing as well as the locus of control in order to understand the organization and its performance. Second, the 'links' in the chain form sequential processing stages that are interdependent with respect to potentially three types of flows; material flows in progressive processing, information flows specifying types and quantity of processes to be performed, and financial flows to reimburse or incentivize the units to devote time and resources to the joint activity. Third, a supply chain is not an arbitrary processing plan but it involves multiple independent organizations (conventionally at least three) cooperating under commercial conditions and subject to actual or potential future competition, both collectively in terms of the final output and individually for each processing stage. Taken together, the three observations underline that *performance evaluation* is of highest importance to assure continuity, competitiveness and, ultimately, survival of the network, but that this evaluation must take into account the specificities of the network character and the decision-making autonomy of the evaluated units.

A wide range of metrics for supply chain performance have been proposed (cf. Melnyk, Stewart, & Swink, 2004; Neely, Gregory, & Platts, 1995) using an equally diverse portfolio of methodologies (cf. Estampe, Lamouri, Paris, & Brahim-Djelloul, 2013). Whereas most SCM literature has been devoted to the elaboration and evaluation of absolute metrics, usually linked to the dimensions cost (profit), time (rates) and flexibility (change of rate), there has also been a growing awareness of the need to perform external benchmarking (Beamon, 1999), the lack of integration of metrics

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(Beamon, 1999; Chan & Qi, 2003), the lack of system's view (Holmberg, 2000) and the lack of non-cost indicators (Beamon, 1999; De Toni & Tonchia, 2001). In response to this critique, several applications of non-parametric frontier analysis, such as Data Envelopment Analysis (DEA), have been proposed for supply chain management. The production-economic foundations and the capacity to derive a consistent set of informative performance metrics for a multi-input and multi-output setting qualify frontier analysis as a useful tool for operation management assessments. However, the interdependencies among evaluated units call for specific frontier models, in particular the multi-stage or network models (cf. Färe & Grosskopf, 1996b). These models explicitly take into account the network structure in the evaluation, deriving metrics that can evaluate both individual unit and chain-wide performance in the long and the short run. However, the rapid development of such models (e.g. Chen & Zhu, 2004; Chen, Cook, Li, & Zhu, 2009, Chen Chen, Liang, Yang, & Zhu, 2009; Chen et al., 2006; Färe & Grosskopf, 2000; Zha & Liang, 2010) and their relevance to supply chain performance assessment have not yet been critically reviewed.

It is to fill this need that this paper summarizes the state-of-the-art in frontier analysis models for supply chain management and their applications, along with identification of future research directions. We put emphasis on a special case of multi-level DEA, commonly called the *two-stage process*. The outline of this paper is organized as follows. In section 2, we discuss the relevant challenges with in SCM in terms of performance assessment. Section 3 is a short recapitulation of DEA definitions for readers not familiar with the models. In Section 4, we present a generic activity model for supply chain evaluation. In Section 5 we review the DEA-models including two-stage structures, models based on cooperative and non-cooperative game theory and the bi-level programming model. The paper is concluded in section 6 with a critical analysis of the reviewed work and some directions for future research.

2. Performance evaluation in supply chain management

In the late 1980s, the term Supply Chain Management (SCM) arose and came into widespread use in the 1990s. SCM has been increasingly developed in theory and practice (e.g. Houlihan, 1985; Jones & Riley, 1987). Generally, supply chain is a system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer. In many cases a supply chain consists of multiple suppliers, manufacturers, wholesalers, retailers. The management of a supply chain can be defined as (Bidgoli, 2010):

The systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.

Supply chain management takes an integrated system's view on the design, monitoring and control of the chain. This approach serves to arbitrate the potential conflicts of individual agents in the chain in order to coordinate the flow of products and services to best serve the ultimate customer. We refer to this framework as "centralized", in that it represents the objective of a hypothetical benevolent supply chain coordinator with authority to implement any necessary decision throughout the chain.

Performance measurement is intrinsically anchored in SCM both as a predictive and normative paradigm. It is *predictive* in the sense that performance management provides productivity estimates useful for the prediction of processing yields and times while planning material and information flows in order to meet stochastic demand, product and process changes. It is also a *normative* paradigm in the sense that supply chain management interfaces with both operations management and sourcing, providing targets for improvement as well as potentially credible threats of substitution or volume reductions in case of poor [relative] performance. A seminal paper in performance measurement design is Neely et al. (1995), defining the scope of performance assessment as the quantification of effectiveness and efficiency of action. The paper also offers an overview over a wide range of techniques and metrics used as well as their limitations and areas for future research. Conventionally, the operations management literature limited the attention to performance measurement to the mere definition of absolute (e.g. cost per unit) and partial productivity (e.g. labor hours per unit produced) metrics (cf. Melnyk et al., 2004 for a critique of this approach or Lambert & Pohlen, 2001 for an example) without paying attention to their systemic or economic integration, or even to their value as predictors of future profitability or survival in the market place. Neely et al. (1995) provide greater nuance to the analysis of supply chain performance by distinguishing the type of measurement, metric and method based on an analysis of organizational level, integration, organizational support, managerial application and hierarchical level. The authors empirically document that firms frequently neglect non-financial data, use internal cost data of varying quality, deploy methods with no or poor connection to organizational strategy and globally are dissatisfied with their performance assessment system. Shepherd and Gunter (2006) review 362 scientific papers on supply chain performance measurement and conclude that the findings of Neely et al. (1995) in many aspects still are valid. Alternative qualitative approaches exist using tools such as balanced scorecards (cf. Bhagwat & Sharma, 2007). However, the information made available from such models is limited in terms of e.g. decomposing productive and cost efficiency. Nevertheless, the need to identify performance in supply chain management can be of strategic as well as operational value, cf. Gunasekaran, Patel, and McGaughey (2004) and Olugu and Wong (2009), leading us to require consistency in the evaluation methodology between the two levels.

Applications of frontier methods, particularly DEA, to complex multi-stage systems, are relatively rare. An early application to US Army recruitment in Charnes et al. (1986) uses a two-stage approach with intermediate outputs forming the basis of later network models. Färe and Grosskopf (1996a) present a network DEA formulation to examine the internal structure of an entity. Talluri, Baker, and Sarkis (1999) propose a framework based on DEA and multi-criteria decision models for value chain network design, primarily aiming at the identification of an optimal supplier-manufacturer dyad. Löthgren and Tambour (1999) use the network DEA model introduced by Färe and Grosskopf (1996a) to estimate efficiency and productivity for a set of Swedish pharmacies. Hoopes, Triantis, and Partangel (2000) develop a goal-programming DEA formulation modeling serial manufacturing processes and apply it to data on circuit board manufacturing. Ross and Droge (2002) propose an integrated benchmarking approach for measuring temporal efficiency using some extensions to DEA methodology and then applying their approach into real data including 102 distribution centers in the petroleum business. Talluri and Baker (2002) propose an interesting three-phase approach for designing an effective supply chain using a DEA framework. Phase I evaluates potential suppliers, manufacturers, and distributors in determining their efficiencies using a combination of DEA models and a pair-wise efficiency game. Phase II contains an integer programming model, which optimally selects candidates for supply chain design using a combination of the efficiencies obtained in phase I, demand and capacity requirements,