European Journal of Operational Research 224 (2013) 313–323

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under uncertainty

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ARTICLE INFO

Article history:
Received 1 November 2011
Accepted 27 August 2012
Available online 8 September 2012

Keywords:
Supply chain
Control
System dynamics
Robustness
Resilience
Adaptation

ABSTRACT

The analysis of how to achieve planned economic performance in a real-time, uncertain and perturbed execution environment is a vital and up-to-date issue in many supply chains. Although it is intuitive that uncertainty is likely to have impacts on performance, the research on systematic terminology and quantitative analysis in this domain is rather limited as compared with the well-established domain of supply chain optimal planning. This study is among the first to address the operative perspective of the supply chain dynamics domain. The methodology of this conceptual paper is based on the business and technical literature analysis and fundamentals of control and systems theory. In contributing to the existing studies in this domain, the paper proposes a possible systemization and classification of related terminology from different theoretical perspectives, and important practical problems. For the supply chain dynamics domain, the paper identifies and groups possible problem classes of research, corresponding quantitative methods, and describes the general mathematical formulations. The results of this study may be of interest to both academics and practitioners.

1. Introduction

It has long been accepted in literature and practice that various sources of uncertainty should be considered during planning supply chain (SC) performance (Acar et al., 2010; Di Giacomo and Patrizi, 2010; Dolgui and Prodhon, 2007; Graves and Willems, 2008; Hendricks and Singhal, 2005; Kleindorfer and Saad, 2005; Klibi et al., 2010; Son and Venkateswaran, 2007; Zhang et al., 2011). At the same time, this performance will be achieved subject to real-time execution dynamics (Ivanov et al., 2012; Sarimveis et al., 2008; Vahdani et al., 2011). Decisions in SC planning and control are therefore interconnected and depend on tackling uncertainties and dynamics.

The practical importance of such integration can be illustrated with some examples. Losses through unplanned (e.g., demand fluctuations) and intentional (e.g., terrorism or theft) perturbation impacts can amount to 30% of annual turnover (Kleindorfer and Saad, 2005; Williams et al., 2008). Perturbations may cause disturbance. In an effort to protect SCs against disturbance, a redundancy of SC structures may typically be created. An example is Dell that combines transport and inventory strategies by storing cheap components in Europe and replenishing expensive components on demand in Asia. Cisco stores expensive components in the USA and produces cheap components in Asia. Another example is the German automotive supplier MTU Aero Engines Ltd., which is able to run production for three weeks, based on safety stocks. First insurance products such as Supply Chain Insurance (SCI) have recently been developed and introduced in practice.

Another possibility for avoiding disturbances is through the coordination and flexibility of the SC. Stevenson and Spring (2007) emphasize that flexible SCs are able to adapt effectively to perturbations and change whilst maintaining output performance (e.g., service level). Various strategies for SC coordination and flexibility – e.g., how to avoid or mitigate the bullwhip-effect – have been discussed by Disney et al. (2006) and Ouyang (2007). Recent advancements in these and other related areas (e.g., capacity uncertainty) have been achieved also in system dynamics (SD) (Barlas and Gunduz, 2011; Georgiadis and Athanasiou, 2010; Sterman, 2000).

As far as the execution stage goes, Mulani and Lee (2002) showed that SC managers spend about 40–60% of their working time handling disruptions. Recent studies by Sheffi (2005) and Datta and Christopher (2011) addressed the problem of SC resilience as being the ability to recover performance after a perturbation. In addition, in recent years, studies on SC dynamics were broadened by developments in information technologies such as RFID (Radio Frequency Identification), SCEM (Supply Chain Event Management) and mobile business, providing a constructive basis on which to incorporate the stages of SC planning and execution control (Lee et al., 2011).

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http://dx.doi.org/10.1016/j.ejor.2012.08.021

Although the domain of SC performance synthesis and analysis in terms of real-time dynamics and uncertainty becomes more and more important in practice, it has received little systematic consideration so far in the literature. Along with the great advantages of recently developed SC optimization approaches, the models as currently implemented in APS (Advanced Planning and Scheduling) and SCM (SC Management) information systems still do not consider important practical operability objectives such as robustness, stability, and flexibility. This situation creates a gap between theory and practice. We regard this shortcoming as an opportunity for research and development, which could significantly improve the practice of SCM.

Although it is intuitive that uncertainty is likely to impact on performance, there is little systematic analysis and documentation of the magnitude of such impact, both (1) at the planning stage while synthesizing SCs regarding uncertainty and analysing these plans with regard to differing execution environments and (2) at the execution control stage while adapting SCs.

Recent studies in both business and technical literature emphasized that SCs need to be considered with regard to dynamic aspects, a real-time performance and perturbed execution environments (Daganzo, 2004; Ivanov et al., 2010; Meepetchdee and Shah, 2007; Santoso et al., 2005; Sheffi, 2005; Springer and Kim, 2010). These studies indicated different approaches to analysing the impact of uncertainty on SC performance, based on the categories of stability, robustness, flexibility, resilience, etc. Nevertheless, there is considerable variation in the definitions of terms related to SC dynamics, uncertainty and performance (Klibi et al., 2010). For example, in business literature these categories are frequently used equivalently in general contexts, while in systems and control theories they have a very specific technical meaning. From this perspective, translating control theory (CT)-based methodology to real-time SC examples is an interesting research avenue for SCM.

Practitioners are very interested in the results of those studies that would help them to estimate investment in different redundancies to mitigate uncertainty and its impact on SC performance. To ensure this, there should be an analysis system that would include clear terminology and quantitative analysis tools. In addition, useful tools for quantitative analysis of control and systems theory for a wide SCM research community remain undiscovered.

This study is among the first that addresses the operative perspective of the SC dynamics domain (as opposed to the in-depth investigation of the strategic risk-management domain). The operative perspective of the SC dynamics domain has been partially considered in previous studies by Craighead et al. (2007), Hendricks and Singhal (2005), Kleindorfer and Saad (2005); a control theoretic study by Sarimveis et al. (2008) on SC dynamic analysis; the studies by Klibi et al. (2010) on robustness in SC design context; and Das (2011) on SC flexibility.

This paper, while not claiming to be encyclopaedic or to create a comprehensive methodology of SC dynamics analysis, has the following *goals*. First, it aims to propose a possible systemization of related terminology from system and control theoretical perspectives and important practical SCM problems. The second goal is to describe the important issues and perspectives that delineate uncertainty and performance in SCM contexts and identify possible problem types for research. Third, it aims to analyse existing tools for synthesis and analysis of performance with regard to uncertainty that can be used in the SCM domain.

In so doing, we are especially interested in the following questions:

- What are the objective properties of SCs regarding uncertainty and performance, and what is the appropriate terminology for their definition?
- What types of problems are typical within SC dynamics analysis and control domains?
- How can these properties and problem classes be interrelated and what can be the classification features that distinguish them?
- Which of those properties can be quantitatively measured, and what techniques or tools can be applied to different types of problem?

The answers to these various questions could be of interest to both academics and practitioners. On the one hand, a systematic representation of SC dynamics domain taxonomy can be used by researchers, e.g., by identifying problem issues in this domain. On the other hand, in improving on systematic interrelations and attracting tools for quantifying them, many practical managerial problems can be approached. For example, how robustness and flexibility influence SC performance both from the cost and benefit points of view can be investigated in a real-time interrupted execution environment. Another issue is the analysis of the attainability of planned SC performance in a real-time execution environment. Finally, SC stability and the impact of different adaptation steps on SC execution behaviour, resilience and performance can be analysed.

The methodology of this conceptual paper is based on literature analysis and the fundamentals of control and systems theory. The remainder of this paper is organized as follows. In Section 2, the related literature is analysed. Section 3 describes the terminological framework and identifies possible research problems. In Section 4, an analysis of quantitative techniques is presented. We conclude the paper in Section 5 by summarizing the main findings and discussing future research.

2. State of the art

One of the main objectives of SCM is to increase total SC output performance, which is basically referred to as SC effectiveness (SC service level) and efficiency (SC costs) (Christopher, 2012). The achievement of SC output performance is the basic imperative for SC design, planning and scheduling (Cohen and Roussel, 2004; Simchi-Levi et al., 2010).

On the other hand, achievement of planned performance can involve the impact of perturbations in a real-time execution environment. SC execution is subject to uncertainty at the planning stage and disruption at the execution stage. As highlighted by Lee (2004), cost efficiency comes with a huge hidden expense should a major disruption (i.e., a more severe impact than a routine disturbance) occur. This requires SC protection against, and efficient reaction to, disturbances/disruptions. Therefore, SCs need to be planned to be *stable, secure, robust and resilient* enough to (1) maintain their basic properties and ensure execution and (2) be able to adapt their behaviour in the case of disturbances in order to achieve planned performance with the help of actions for recovery.

2.1. Robustness, stability, security: using redundancies to avoid disturbances

Recent literature has identified different methods to strengthen SCs in order to mitigate the impact of uncertainty. In mathematical programming (MP), uncertainty of future execution is typically considered with the help of stochastic and robust optimization, where possible deviations in control variables are addressed, either with probability estimation or interval data. Whilst stochastic optimization tends to be applied to large and middle-sized planning horizons (e.g., Mula et al., 2010; Santoso et al., 2005), robust optimization can also be applied to tactical–operative planning (Klibi