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Optimal control representation of the mathematical programming model for supply chain dynamic reconfiguration

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Abstract: In this article, we develop an optimal control model of supply chain reconfiguration that has been previously investigated with the help of mathematical programming approach. The developed model can be used to represent the dynamics of a continuous-flow supply chain system with a hybrid discrete-continuous state space. Dynamics of the supply chain reconfiguration can be modelled more detailed using the aggregate optimal parameters determined in the mathematical programming representation. The results of this study allow to distribute parameters and variables between mathematical programming and optimal control models in order to exploit their advantages in a joint manner. Copyright © 2017 IFAC

Keywords: control, supply chain, mathematical programming, dynamics

1. INTRODUCTION

Dynamics is one of the underlying challenges in supply chain (SC) management. One of the substantiated issues in SC dynamics is the ability to change (adapt) in dynamic environments in case of severe disruptions. This problem has been extensively studied in the literature from various strategic, tactical and operative perspectives in light of numerous severe disruptions such as tsunami in Japan in 2011 and floods in Thailand in 2011. With increasing frequency of severe disruptions, research on severe disruptions in SCs has become an important focal area for research and industry.

In literature, mathematical programming (MP) methods dominate the quantitative research on supply chain optimization with disruption considerations. MP models provide interesting managerial insights and can be successfully used in the cases where disruption probabilities can be fairly estimated and the impact of the disruption on the SC financial performance such as lost sales or revenues can be determined straightforward. However, in many situations it is possible to adjust the SC flows and recover after a disruption. That is why the performance impact can be mitigated by SC reconfiguration.

In addition, the models on SC disruption management typically include such parameters as disruption time and recovery time (Simchi-Levi et al. 2015). These time-dependent issues are difficult to resolve within an MP model without complexity increase. Moreover, the dynamic change of SC operational parameters such as capacity and inventory make it difficult to hood the MP models in a reasonable size. One of the possible ways to resolve the time issues in MP models is to perform a discretization in some intervals of SC structural constancy (Ivanov et al. 2016a). However, the efficient computation is possible in this situation using only a limited number of aggregated parameters such as processing capacity or inventory. In reality, the models need to consider much more detailed parameters such as product heterogeneity and different priorities of customer orders in regard to their importance and urgency. To the best of our knowledge, there is no published research on the development of an optimal control analogy of the MP model in regard to SC re-planning.

In order to close this research gap, in this article, we develop an optimal control model of supply chain reconfiguration that has been previously investigated with the help of MP approach. The develop model can be used to represent the dynamics of a continuous-flow supply chain system with a hybrid discrete-continuous state space. Dynamics of the supply chain reconfiguration can be modelled more detailed using the aggregate optimal parameters determined in the mathematical programming representation. This allows to distribute parameters and variables between mathematical programming and optimal control models in order to exploit their advantages in a joint manner.

2. STATE-OF-THE-ART

In this section, we analyse literature on MP and optimal control applications to SC disruption management with reconfiguration. Recent reviews can be found in Fahimnia et al. (2015) and Ivanov et al. (2015). Since the scope of our study is on SC dynamic reconfiguration, we restrict ourselves to this research stream only. In regard to optimal control, the applications to SC disruption management are quite limited. That is why we include in literature analysis optimal control applications to SC, production and logistics dynamics in the broader sense.

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2.1. Mathematical programming

For the analysis we selected the recent studies that address multi-period, multi-stage SCs with time-dependent disruption considerations and recovery policies. Losada et al. (2012) use a bilevel MIP for protecting an uncapacitated median type facility network against worst-case losses. The role of facility recovery time on system performance and the possibility of multiple disruptions over time is considered. Rafiei et al. (2013) developed a model for a problem statement with multiple products and many periods. They considered the levels of inventory, back-ordering, available machine capacity and labour levels for each source, transportation capacity at each transhipment node and available warehouse space at each destination. The problem also considered the facility fortification by taking into account the back-up supplier with reserved capacity and a back-up transhipment node that satisfied demands at higher prices without disruption facility. The solution to the model is based on a priority-based genetic algorithm.

Constantino et al. (2012) presented a hierarchical approach to the strategic supply chain design addressing supply planning and allowing the improvement of the manufacturing supply chain agility in terms of ability in reconfiguration to meet performance, and considering the supplier capacity constraints. The approach employs digraph modeling and integer LP to optimal supply chain design. The authors avoid stochastic models by aggregating deterministic product flows within the integer LP model.

Sawik (2016) developed a stochastic programming model to integrated supplier selection, order quantity allocation and customer order scheduling in the presence of SC disruption risks. In the study by Madadi et al. (2014), a problem of supply network design under risk of supply disruptions is considered. Tainted materials delivery disruptions are modeled as events which occur randomly and may have a random length. A mixed-integer stochastic model is proposed and solved by a meta-heuristic algorithm.

2.2. Optimal control

SCs are dynamic systems subject to both structural (e.g., because of ripple effect resulting from severe disruptions) and parametrical (e.g., demand fluctuations) changes (Ivanov et al. 2012, 2016b). Control theory (CT) as a base for studying multi-stage, multi-period dynamic systems is an interesting research avenue to extend existing results while taking into account the intrinsic peculiarities of modern SCs. CT contains a rigor quantitative basis for planning optimal control policies including differential games and stochastic systems, stability of controlled processes and non-linear systems, controllability and observability, and adaptation (Disney and Towill 2002; Ivanov et al. 2016b,). These tools can be applied for a wide range of systems, from discrete linear to stochastic non-linear systems with both stable and dynamically changing structures. CT can also be applied for analysis of equilibriums of resource consumption and system output.

Applications of CT, simulation and systems science to SC dynamics are multi-faceted. Ortega and Lin (2004), Disney et al. (2006) underline the resemblance of SCs to engineering dynamic systems. In recent decade, control and adaptive approaches to SC optimization received more and more attention in scientific community.

Applications of MPC (model-predictive control) to multi-echelon production–inventory problems and SCs have been examined previously in the literature. Perea et al. (2000) modelled multi-plant, multi-product polymer processes through difference equations, and schedule optimization in an MPC framework. Braun et al. (2003) developed a decentralized MPC implementation for a six-node, two-product, and three-echelon demand network problem. In the study by Ivanov and Sokolov (2012), an optimal control SC scheduling model has been developed. The solution procedure is based on a combined application of maximum principle and linear optimization. Ivanov et al. (2013, 2014) developed a model for multi-period and multi-commodity SCD with structure dynamics considerations. The original idea of these studies is the SC description as a non-stationary dynamic control system along with a linear programming (LP) model. In contrast to MIP formulation, they distribute static and dynamic parameters between the LP and control models. Mastragostino et al. (2014) analysed SC performance in the presence of uncertainty in the model parameter and demand considering service level in the SC.

Sagawa and Nagano (2015) use a dynamic approach to modeling the dynamics of a multi-product manufacturing system in a real case application. Yang and Fan (2016) compare the disruption mitigation effects of three information management strategies with the help of control theory. From the aspect of stability, the existing stability boundaries are revised by a new method in a two-echelon case. Ivanov et al. (2015b) study dynamic planning decisions of a logistics service provider that is in charge of the integrated SC planning. They examine an SC with multiple products, suppliers, transit nodes, and customers in a multi-period mode. The logistics service provider is responsible for aggregate distribution planning and operative dynamic transportation planning. To resolve this problem, a hybrid multi-period, multi-commodity distribution–transportation model as an optimal control problem blended with MP has been developed.

Spiegler et al. (2012 and 2015) developed methods to use nonlinear control theory in the dynamic analysis of supply chain resilience in an empirical context of a grocery supply chain and analyse the value of nonlinear control theory to investigate the underlying SC dynamics. The developed method provides insights into the nonlinear system control structures, including a better understanding of the influence of control parameters on dynamic behavior and the impact of nonlinearities on supply chain performance. Klug (2016) analyses bullwhip and backlash effects in the SC with the help of phase space trajectories.

It can be observed in literature that MP models tend to work on the aggregate flow level whilst control models tend to consider detailed flow dynamics. Summarizing, MP research along with control theory contain a number of useful methods that can be used for the proposed research. Different methods are suited to different problems. No single technique is likely