



Decentralized and centralized model predictive control to reduce the bullwhip effect in supply chain management[☆]



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ABSTRACT

Mitigating the bullwhip effect is one of crucial problems in supply chain management. In this research, centralized and decentralized model predictive control strategies are applied to control inventory positions and to reduce the bullwhip effect in a benchmark four-echelon supply chain. The supply chain under consideration is described by discrete dynamic models characterized by balance equations on product and information flows with an ordering policy serving as the control schemes. In the decentralized control strategy, a MPC-EPSAC (Extended Prediction Self-Adaptive Control) approach is used to predict the changes in the inventory position levels. A closed-form solution of an optimal ordering decision for each echelon is obtained by locally minimizing a cost function, which consists of the errors between predicted inventory position levels and their setpoints, and a weighting function that penalizes orders. The single model predictive controller used in centralized control strategy optimizes globally and finds an optimal ordering policy for each echelon. The controller relies on a linear discrete-time state-space model to predict system outputs. But the predictions are approached by either of two multi-step predictors depending on whether the states of the controller model are directly observed or not. The objective function takes a quadratic form and thus the resulting optimization problem can be solved via standard quadratic programming method. The comparisons on performances of the two MPC strategies are illustrated with a numerical example.

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1. Introduction

A supply chain network is an integrated manufacturing process with highly interconnected facilities and distribution channels that function together to acquire raw materials, transform raw materials into intermediate and final products, and deliver final products to retailers (Beamon, 1998). Such a supply chain can be represented by a directed graph composed of nodes and arrows. Supply chain management (SCM), or supply chain optimization, is a set of approaches utilized to efficiently integrate suppliers, manufacturers, distributors and retailers, so that goods are produced and distributed in the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements (Aghezzaf, Sitompul, & Van Den Broecke, 2011; Simchi-Levi, Kaminski, & Simchi-Levi, 1999).

The decisions in SCM are classified into three categories with respect to their impact and time scale: strategic planning, tactical

planning and operational level (Aghezzaf, Sitompul, & Najid, 2010). However, in the major part of the literature SCM employed only heuristics or mathematical programming techniques for simplified representations of the real process (Beamon, 1998; Mestan, Turkey, & Arkun, 2006). It is becoming increasingly difficult for companies to compete on a global scale with only heuristic decisions on simplified representations. In many corporations, management has reached the conclusion that optimizing the product flows cannot be achieved without applying a systematic approach to the business. More and more methods and techniques from control engineering are now utilized to design SCM strategies for accomplishing various goals. The approach this research advocates is to develop decision policies based on a control oriented formulation. The reader is referred to several excellent review papers on the application of classical control theory to the SCM problems (Hoberg, Thonemann, & Bradley, 2007; Ortega & Lin, 2004; Sarimveis, Patrinos, Tarantilis, & Kiranoudis, 2008; Subramanian, Rawlings, Maravelias, Flores-Cerrillo, & Megan, 2013).

Viewed as a complex network, there are many aspects to research in SCM. One of these is the improvement of inventory management policies, the goal of which is to maintain the

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inventory level at each node of supply chain to satisfy the demands from its customer by ordering products from the upstream echelons. A possible approach to these tactical and operational problems can be devised by using model predictive control (MPC). Recent studies utilizing model predictive control have been found to provide an attractive solution for SCM. The philosophy of this application is shown in Fig. 1. MPC was first applied to inventory management by Kapsiotis and Tzafestas (1992) for a single manufacturing site problem. This development has subsequently led to an increasing number of studies on the application of MPC in the last decade (Alessandri, Gaggero, & Tonelli, 2011; Braun, Rivera, Flores, Carlyle, & Kempf, 2003; Ferramosca, Limona, Alvarado, & Camacho, 2013; Li & Marlin, 2009; Lin, Jang, & Wong, 2005; Maestre, Munoz de la Pena, & Camacho, 2011; Perea-Lopez, Ydstie, & Grossmann, 2003; Wang & Rivera, 2008). As can be seen from literature there are several advantages of applying MPC to SCM. The MPC controller achieves the operational objectives of tracking inventory level target and meeting customers' demand. Moreover, it can optimize a cost function that indicates a proper measure for supply chain performance. In addition, MPC shows an improvement in reducing demand amplification or bullwhip effect over classical methods (Dejonckheere, Disney, Lambrecht, & Towill, 2003; Lin, Wong, Jang, Shieh, & Chu, 2004; Towill, Zhou, & Disney, 2007; Warburton & Disney, 2007). The cited studies in literature are different as follows: (1) Models that are specific to the studied problems are developed. For example, Wang and Rivera (2008) examined the application of MPC to inventory control problems arising in semiconductor manufacturing industry. Lin et al. (2005) presented a Minimum Variance Control for a single node system with two separate setpoints for the inventory level and WIP level. Maestre, Munoz de la Pena, and Camacho (2011) developed a distributed MPC algorithm for a two-node supply chain. Their method is not extendable to supply chain network with more than 2 nodes. (2) MPC is used as a tool to maximize operational profit of supply chain ignoring control theoretic performances. Perea-Lopez et al. (2003) employed MPC to a multi-echelon, multi-product supply chain with deterministic demand in order to optimize a cost function that is related to the economic performance measures. (3) The control efforts, e.g., ordering policy, factory starts or transfer of the products, are chosen differently depending on different MPC frameworks and models used. (4) The tailoring MPC algorithms are developed for their specific problems. e.g., Alessandri et al. (2011) combined min–max optimization and MPC to solve inventory control problems for a multi-echelon, multi-product distribution network.

Reducing the bullwhip effect in the context of MPC has been disregarded in most of the previous studies. In contrast, this paper

focuses on MPC as a general method for mitigating the bullwhip effect. The purpose is to demonstrate and compare the applications of customized decentralized and centralized MPC strategies to the benchmark supply chain network and to reduce the bullwhip effect in supply chain operations. The decentralized approach to MPC is formulated to facilitate the development of closed-form transfer function for the ordering policy and the bullwhip is effectively suppressed compared to traditional ordering policies. A frequently suggested method for bullwhip mitigation is to centralize demand information. To further reduce the bullwhip effect, a centralized approach to MPC is proposed despite it is feasible for the supply chain where all nodes belong to one enterprise. With this implementation, optimized ordering decisions are made and the bullwhip effect is eased to a greater extent compared to decentralized MPC ordering policy. This control strategy also has flexibility to put different emphasises on reducing bullwhip for different echelons by assigning proper weights to control move suppression term of objective function.

The remainder of the paper is structured as follows. After introducing the dynamic behaviour and the detailed modelling of the benchmark supply chain in Section 2, Sections 3 and 4 discuss the development of decentralized and centralized MPC frameworks in supply chain management respectively. The effectiveness of the resulting approaches is demonstrated via a numerical example in Section 5. Finally, Section 6 summarizes the major conclusions.

2. Problem description

Consider a serial supply chain model similar to the benchmark system used in Hoberg et al. (2007), Sundar and Lakshminarayanan (2008) and Wright and Yuan (2008). The system depicted in Figs. 2 and 4 consists of 4 logistic echelons, a factory, a distributor, a wholesaler, and a retailer. This type of systems is typical of the predominant real supply chain networks. Orders for products propagate upstream from right to left, and products are shipped downstream in the opposite direction. Although real-life supply chains tend to be multi-product, multi-echelon supply networks, the operational decisions are made for each stock keeping unit (SKU). Thus running supply chain for one product at a time would still be valid. The supply chain with one node at each echelon is studied, but the method can be easily extended to the case of multiple nodes at the expense of extra computational effort.

2.1. General model

For sake of simplicity, it is assumed that operational decisions are made within equally spaced time periods, e.g. hours, days, or

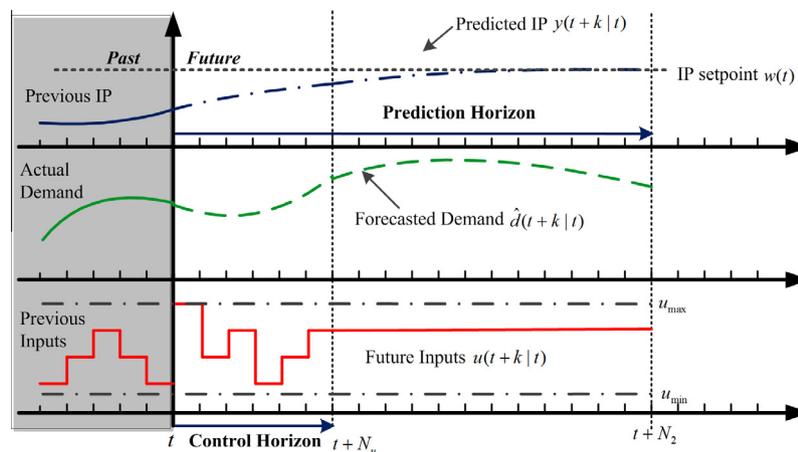


Fig. 1. Visualization on MPC principles to SCM problem.

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