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A process control approach to tactical inventory management in production-inventory systems

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ABSTRACT

Supply chain management (SCM) is concerned with the efficient movement of goods through a network of suppliers and retailers. As delayed and uncertain dynamical systems, supply chains provide an excellent opportunity for demonstrating the benefits of control engineering principles to what is traditionally perceived as a "business" problem. This paper presents a fundamental yet practical approach for applying control-theoretic principles to tactical inventory management problem in a production-inventory system, the basic unit in a supply chain. Beginning with the use of a fluid analogy, we present internal model control (IMC) and model predictive control (MPC) as means for generating a series of increasingly sophisticated decision policies for inventory management. A combined feedback-feedforward multi-degree-of-freedom IMC policy is shown to properly adjust factory starts in the presence of inventory target changes, forecasted shifts in customer demand, and stochastic changes in demand. The MPC policy displays equivalent performance, but incorporates the added functionality of managing inventory in the presence of constraints, an important practical consideration. The MPC policy shows improved performance, greater flexibility, and higher functionality relative to an advanced order-up-to policy based on control engineering principles found in the literature.

1. Introduction

As manufacturing enterprises move ahead in the 21st century, it is becoming increasingly difficult to compete on a global scale without strong inventory management strategies. The effectiveness of an otherwise innovative enterprise is limited if it is unable to deliver a desired product to customers at the correct time, to the right place, and in sufficient quantity. Therefore, production decisions must be quick, robust to uncertainty in the business environment, and optimized to meet key supply chain objectives. Improved inventory management contributes to increased revenues, lower costs, and greater customer satisfaction. There are wider societal benefits to more efficient inventory management as well. For example, minimizing the amount of unsold product reduces waste and the environmental impact of the production process, both in terms of raw materials and energy consumption. This paper presents a series of control-oriented tactical decision policies for managing inventory in production-inventory systems that ultimately seeks to advance these aims.

The study of inventory management techniques in enterprise systems has increased dramatically over the last half century (Whitin, 1970; Buffa and Miller, 1979; Seierstad and Sydsæter, 1987). The use of optimization techniques in the management of supply/demand networks began with the development of the classical Economic Order Quantity (EOQ) approaches (Wilson, 1934; Arrow et al., 1951). Since then, decision polices have been developed to accommodate dynamics (Wagner and Whitin, 1958), production costs, and inventory costs (Holt et al., 1960). Later developments include simulation-based optimization approaches for determining optimal base stock levels in "order-up-to" policies (Glasserman and Tayur, 1995; Kapuscinski and Tayur, 1998) and the application of optimal control theory (Thompson and Sethi, 1980; Sethi and Thompson, 2000) to obtain closed-form expressions for the optimal production rate. Additional control-oriented interpretations and formulations of inventory management policies have been proposed (Grubbström and Wikner, 1996; Riddalls and Bennett, 2002) with strong emphasis on mitigating demand amplification or the "bullwhip" effect (Dejonckheere et al., 2002, 2003; Towill et al., 2007; Warburton and Disney, 2007). The use of model predictive control has been popular as it offers the opportunity to robustly optimize inventories while satisfying constraints (Tzafestas et al., 1997; Perea-López et al., 2003; Braun et al., 2003; Seferlis and Giannelos, 2004; Aggelogiannaki et al., 2008). A number of excellent review articles address the application of control theory to the problem

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space of supply chains and production-inventory systems; these include Ortega and Lin (2004) and Sarimveis et al. (2008).

This paper is focused on how decision policies inspired from process control can be effectively applied for production-inventory and supply chain inventory management problems in uncertain, stochastic environments, as is typically the case in industrial practice. The basis for our analysis is the recognition that supply chain networks can be modeled as delayed dynamical systems. Consequently a control systems approach has significant appeal because, in contrast to classical EOQ approaches, the delayed dynamics of the system are fully incorporated in developing a decision policy. This parallels what is seen in the chemical industries, where process control systems are widely used to adjust flows to maintain level and product compositions at desired values (Ogunnaike and Ray, 1994; Seborg et al., 2004). By applying an abstraction, material flows in high-volume, discrete-parts manufacturing supply chains can be effectively modeled using a fluid analogy; one can therefore expect that decision policies based on process control principles can have a large impact on production-inventory systems and consequently, supply chain management.

A fluid representation of a production-inventory system is shown in Fig. 1. Here the manufacturing node is represented as a "pipe", while the warehouse node is represented as a "tank". Material in the pipe and tank corresponds to work-in-progress (WIP) and inventory, respectively. Specifically, in this paper we consider process control techniques such as internal model control (IMC) (Morari and Zafiriou, 1988) and model predictive control (MPC) (García et al., 1989; Camacho and Bordons, 1999) as decision policies that can provide improved performance in manufacturing systems with long throughput times and significant uncertainty, such as semiconductor manufacturing (Kempf, 2004). As control-oriented frameworks, IMC and MPC-based decision policies have the advantage that they can be tuned to provide acceptable performance in the presence of significant supply and demand variability and forecast error as well as constraints on production, inventory levels, and shipping capacity. Ultimately, the improved decision-making resulting from the application of these policies will lead to lower manufacturing costs while maximizing revenue and improving customer satisfaction.

The authors' previous work involved the development of novel model predictive control strategies for tactical decision-making in semiconductor manufacturing supply chains (Wang et al., 2007; Wang and Rivera, 2008), the optimization of these policies to meet financial objectives in a stochastic environment (Schwartz et al., 2006), and the generation of control-relevant demand forecasts tailored to these policies (Schwartz and Rivera, 2006, 2009; Schwartz et al., 2009). This paper takes a different approach. First, we focus on a standard production-inventory system and develop a series of control-oriented tactical decision policies "from the ground up," justifying for each one the distinctive functionality and unique insights brought about by applying a process control perspective. Among these include the need to apply *both* feedback and feedforward decision-making in supply chains, and the benefits of a multi-degree-of-freedom formulation for independently addressing varied supply chain requirements such as building net stock, meeting anticipated demand, and maintaining inventory in the presence of uncertain demand. The MPC decision policy is compared with a state of the art "order-up-to" policy developed by Dejonckheere et al. (2003) that is formulated using control engineering principles. By focusing on the systematic development of various control algorithms and their application on a common benchmark problem, we hope this paper will both inform the supply chain management community, and encourage greater implementation of control-oriented inventory management policies in practice.

The paper begins in Section 2 with a mathematical description of a fluid analogy for a production-inventory system. This fluid analogy forms the nominal model for the process control oriented tactical decision policies. Section 3 presents the design and application of proportional-integral-derivative (PID) control, multi-degree-of-freedom IMC, and MPC, respectively, to the control of the production-inventory system. In Section 4, the MPC decision policy is compared with the policy developed by Dejonckheere et al. (2003). Summary and conclusions are presented in Section 5.

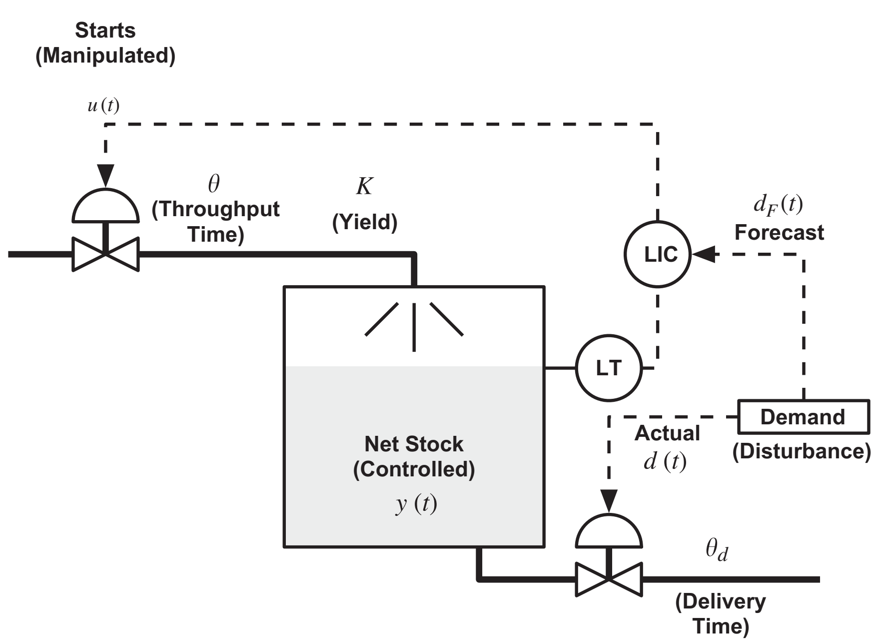

Fig. 1. Fluid analogy for a classical production-inventory system.