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Inventory control for the supply chain: An adaptive control approach based on the identification of the lead-time

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ABSTRACT

In this paper, an Internal Model Control (IMC) scheme is incorporated in production inventory control systems in a complete supply chain. This control scheme presents a good target inventory tracking under the perfect knowledge of the system. Furthermore, the inventory tracking and load disturbance rejection control problems can be tackled separately. However, the closed-loop performance of the IMC scheme may be degraded due to a mismatch between the modelled and actual delay or to the fact that delays may be time-varying. Thus, the IMC control scheme is enhanced in this work with a novel method for the online identification of lead times based on a multimodel scheme. In this way, all benefits of the IMC scheme can be exploited. A detailed discussion of the proposed production inventory system is provided including a stability and performance analysis as well as the identification capabilities of the algorithm. Several simulation examples illustrate the efficiency of the approach.

1. Introduction

A common supply chain (SC) includes the necessary entities to provide goods to the customer from production centers. Thus, the main elements composing a general supply chain between the factory (F) and customer (C) are: warehouse (W), distributing center (D) and retailer (R) [1,2]. There are many participants and processes as well as randomness in the information flow of a supply chain. Therefore, the coordination of the supply chain operation becomes a key point to optimise the use of its resources and compete on a global scale. There are many aspects to research in this complex network, one of these is the improvement of inventory management policies. The main objective of inventory management is to keep the inventory level of each element of the supply chain stable enough so as to satisfy the requirements of the customers by ordering products from its immediate supplier of the supply chain [3]. In this way, the supply chain is modeled as a serial process where each element gives orders to its immediate supplier in order to have enough goods to supply the orders of the immediate customer of the chain. The entire supply chain is a serial process since one element is strictly related to its immediate downstream and upstream elements. This kind of processes are commonly described as multi-variable (Multiple Inputs – Multiple Outputs) systems and they are represented by a matrix with a block diagonal structure [4]. Once an order is placed on the immediate supplier there is a time to the moment that the petition is satisfied. This is known as replenishment lead time and it consists of an ordering time-delay and a production or distribution time delay [5]. Many undesirable effects may appear when an inventory replenishment policy is implemented in the supply chain described above. Among these, the instability is the main problem since signals describing the inventory and orders may diverge as time goes on. Hoberg et al. [6] applies linear control theory to study the effect of several inventory policies on order and inventory variability (using z-transform techniques) and their conditions for stability are examined by the Jury criteria.

Another inconvenience is that the variability in the ordering patterns often increases as we move upwards in the chain, from the customer to the factory and the suppliers. This phenomenon is broadly known as the *bullwhip effect*. Some current studies [1,2,6,7], have analyzed the effect of the replenishment policies focused on the bullwhip effect estimation and suppression. Moreover, Lin et al. [3] presents Control Engineering based approaches, including proportional-integral (PI) controllers and cascade control as inventory replenishment policies, being the design of this controller also focused on the mitigation of the bullwhip effect. Balan et al. [8] applies fuzzy logic theory control on inventory error and error changes associated with forecast demand among the nodes of a supply chain in order to allow smooth information flow in the chain.

Besides stability issues and bullwhip, the response of the net stock signal is an additional important subject of investigation. Tang [9] focuses on base-stock inventory models with and without expected demand and provides a computationally efficient

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method to set optimal inventory targets for finished products under capacitated postponement. Silver and Bischak [10] considers a periodic review order-up-to-level (orbasestock) inventory control system under normal distributed demand. A major problem is inventory deficit existence (i.e. the difference between inventory target and the actual inventory level), usually referred to as inventory drift.

One of the main causes of all these phenomena is attributed to the lead time, specially when it is not properly known. Therefore, counteracting the lead time effect is crucial so as to improve supply chain management. There are two approaches towards the control of systems with external delays. The first one is the robust control approach that consists in designing a controller based on a nominal value for the delay and considering a grade of robustness of the controller to any mismatch in it. In this way, Aggelogiannaki and Sarimveis [11], Schwartz et al. [12], Schwartz and Rivera [13] introduce the Internal Model Control which is a robust control approach, and predictive control as novel decision replenishment policies. These works only consider an approximation of the delay to set up the control problem resulting in a good control of the inventory level avoiding the bullwhip effect. However, the changes in the delay through the time which is a typical situation in the supply chains are not considered in this approach.

A second control approach that allows us to tackle systems with delay without considering any approximation is the use of delay compensation schemes. The Smith Predictor (SP) and its generalizations such as those based on the Internal Model Control (IMC) are the more extended configurations [14]. These topologies were proposed in the 50 s and they have been extended to include robustness issues or the possibility of dealing with unstable processes [15] ever since. In this work we advocate on a decentralized control approach based on an IMC delay compensation scheme for the MIMO supply chain. One of the main advantages of the use of an IMC type structure is that in this scheme there are three controllers that allow to tackle the nominal stability, the relation (Inventory level vs Inventory target) and the relation (Inventory level vs Demand) separately. The use of the delay compensation scheme facilitates the controller design because it allows to disregard the delay when designing two of these controllers, which is an advantage in the design process.

However, delay compensation schemes have a drawback: the system's delay has to be known beforehand to perform its perfect compensation. This situation is not viable when the delay changes during the process which is a common situation in supply chains. An alternative to overcome this problem is to include a lead time identification method in the supply chain operation.

It is difficult to find works that deal with lead time identification in entire supply chains since most of works normally deal with a single echelon. In Aggelogiannaki and Sarimveis [11] a recursive prediction error method (RPEM) is proposed to identify the lead time online in a unique echelon (SISO system), based on historical data that includes order rate and received final products. Then one parameter of an Automatic Pipeline, Inventory and Order Based Production Control System (APIOBPCS) is adjusted according the identified lead time. On the other hand, some researchers have developed algorithms from a control theoretic perspective for online identification and adaptive control of delayed MIMO systems, (see, for instance [16–18]). In Bernstein and Rad [16], a time-delay neural networks (NNs) model is employed to perform simultaneous system identification and time-delay estimation. The proposed network, for which stability is proved using Lyapunov theory, is an extended version of the delay-free dynamical NN. The adaptive controller, Mirkin and Gutman [17] presents a simple model reference adaptive control (MRAC) scheme which is also robust when dealing with external disturbance with unknown bound. A suitable Lyapunov–Krasovskii type functional with "virtual" gain is used to design the adaptation algorithm and prove stability. In Chen et al. [18], a novel adaptive neural controller based on a NN online approximation model is proposed. Its main contribution consists of the construction of a quadratic-type Lyapunov–Krasovskii functional which results in a number of online-adapted parameters independent from the number of nodes of the neural network which reduces complexity. Other significant results on this control issue have been reported in Ge [19], Zhang and Ge [20] and Zhang and Ge [20]. Overall, an important disadvantage of the aforementioned works is the large number of involved parameters and their theoretical complexity. Moreover, none of them have ever been applied to the supply chain control problem. In fact, there is no supply chain application of these delay identification works to lead time estimation. In this work, a delay identification algorithm is proposed for the complete supply chain being able to identify the delays among the different echelons describing the supply chain. The identified values of the delays are then used to adjust the delay compensation in a IMC based decentralized compensation scheme. The proposed identification scheme is based in a multi-model scheme, it made up of a battery of different models operating in parallel [21–23]. Each model includes the same rational component but a different delay value. A supervisory algorithm compares the mismatch between the actual system and each candidate models and it determines, for each time interval, the one that best describes the behaviour of the real system, providing an estimation of the lead time. An additional block selects the best model for control purposes. The approach is inspired in what are called Pattern Search Algorithms [24], whose application in control is really novel. Besides the formulation of the complete control scheme. In the present work, theoretical proofs to guarantee that the algorithm identifies the real lead times of the supply chain and closed-loop stability are provided, which is not common in works aimed at inventory control in the supply chain. Indeed, these proofs are conceptually easier than those presented in the mentioned works. The rest of the paper is formulated as follows: Section 2 presents the complete supply chain model using *z*-transform. As a result, a discrete multiple input multiple output (MIMO) system is obtained. Section 3 presents the formulation of the Internal model control as a delay compensation scheme to inventory control in supply chains. After that, Section 4 presents the adopted intelligent multimodel identification scheme. Section 5 presents theoretical results that ensure its convergence to the real lead time and the closed-loop stability, being the proofs of lemmas and theorems in the Appendix. Section 6 presents the simulation results. The paper ends with the concluding remarks in Section 7.

2. Supply chain model

Let us consider a general supply chain model used in Dejonckheere et al. [1], Hoberg [6]. For the sake of simplicity, assume a period base of time $T_m=1$ which can be one day, one week or one month according to the dynamics of the supply chain. In this model there are three logistic echelons, warehouse (W), distributing center (D) and retailer (R) between the factory (F) and customer (C) as is shown in Fig. 1. The customer is considered to be the base of supply chain while the Factory is on the top of the supply chain. Thus, denote by $j=0,1,2,3,4$ each of the logistic echelons of the supply chain. Thereby, for this specific supply chain $j=0$ represent the Customer (C) and $j=4$ represents the Factory (F). According to this notation, $(j+1)$ represent an immediate supplier and $(j-1)$ represent an immediate customer. The scheme of the supply chain in consideration is shown in Fig. 1.