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► **To cite this version:**

Danielle Nyakam Nya, Hassane Abouaïssa. Adaptive Model-Free Control for Robust and Dynamic Management of Perishable Products\*. IEEE-IFAC, 9th International Conference on Control, Decision and Information Technologies (CoDIT'23), Jun 2023, Roma, Italy. hal-04236327

**HAL Id: hal-04236327**

**<https://univ-artois.hal.science/hal-04236327v1>**

Submitted on 10 Oct 2023

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# Adaptive Model-Free Control for Robust and Dynamic Management of Perishable Products\*

Danielle Nyakam Nya and Hassane Abouaïssa<sup>1</sup>

**Abstract**—This paper investigates the controller design for a robust and efficient supply strategy for logistic constrained systems with perishable goods subject to uncertainties on the demand and the process delays. Here, instead of model-based control strategies, through a continuous, local identification of the level variations and forecasting via the setting of time series, an adaptive model-free control that does not need any prior knowledge of the supply chain behaviors is developed. The proposed approach takes into accounts not only the decay of goods stored in warehouse (perishing inventories) and prevents from exceeding the facilities capacities but also ensures full demand satisfaction irrespective of the value of delay and reacting significantly faster to the consumer’s demand uncertainty. Quantitative analyzes prove a strong reduction of the storage cost, increase of the profit and bullwhip effect attenuation.

**Keywords**— Adaptive Model-free control, supply chains, time-delay systems, perishable products, inventory control, forecasting, algebraic estimation.

## I. INTRODUCTION

Since the last two decades, the studies of supply chain systems and their dynamic management have become a hot topic for both academic researchers and industrial practitioners. Several approaches from operations research or control theory have been proposed to address the various aspects of supply chains problems. Tactical inventory management in production-inventory system, which is the basic unit in supply chain has recently gained several attention and several interesting contributions have been reported in literature ranging from deterministic to highly complex stochastic methods (See e.g., [5], [21], [26], [27], [30], [31], [32], [33], [35], [40], [41], [45], [46], [47] and the references therein). It is important to emphasize that most of the approaches to dynamic inventory management are model-based one. The efficiency of the model-based control algorithm is closely related to the quality of the mathematical model of system, which becomes even more complex in the case of a supply chain with perishable products. Indeed, the particular case of perishable inventory control (PIC) represents a protruding problem in the supply chain management frame. Generally, the inventory management objective is the design of a system to control and monitor the different levels of the studied supply chains continuously and periodically assuming unlimited lifespans of the different products [22]. However, most of the products become unfit for consumption when their shelf-lives

are exceeded. As mentioned in [13], the worth of the wasted food is in the billions of dollars annually. Perishable products concern not only food but also cut flowers, pharmaceuticals products, blood, chemicals, which are with a limited shelf-time. Companies loss may grow significantly because of this finite shelf-life after which products get outdated and have to be disposed. Some portions of manufactured products go into waste before customers purchase it, see Fig. 1.

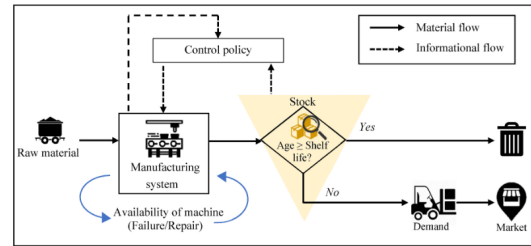


Fig. 1. Example of manufacturing system with perishable products [22]

In this fields several approaches are consecrated to the Perishable Inventory Management (PIM) problem were the consumers demand are taking into account. Markov dynamic programming, simulation approaches, methods stemming from optimization techniques [23] are among the several approaches used in PIM problems such as the study of blood bank [14]. Others approaches stemming from control theory have been largely studied for perishable products (See for example [4], [5], [23], [24] [25], [38], [44]), to answer the typical question: *What are the optimal time and volume of the order, that best satisfy the customer demand, while accounting for product perishability?* [22]. The complexity of PIM is enhanced with the uncertainty demand variations overtime often due to variable market conditions as commonly happens in modern supply chains. This leads to inventories replenishment with a no negligible delay, which make control design problem cumbersome in this situation. When an order is placing, in order to maintain high service level and at the same time keep stringent cost discipline, it is necessary not only to account for the demand during procurement latency but also for the stock deterioration in that time. Therefore, an effective dynamic management should lead the coordination of supply chain operation to optimize the use of its resources to obtain lower inventory, production, transportation and location cost, the fast reaction to customer’s demand variation and the bullwhip effect <sup>1</sup>[20]

\*This work was supported by Region de Hauts-de-France

<sup>1</sup>Danielle Nyakam Nya and Hassane Abouaïssa are with Univ. Artois, UR 3926, Laboratoire de Génie Informatique et d’Automatique de l’Artois (LGI2A) F-62400 Béthune, France (danielle.nyakamnya, hassane.abouaïssa)@univ-artois.fr

<sup>1</sup>Bullwhip effect is the variability in the ordering patterns often increases as we move up into the chain, from the customer towards the suppliers and factory

and emulate on a global scale (providing customers the right product, in the right quantity, at the right time, for the right price, and at the right place [6]). However, the complexity of modern supply chains makes their modeling very difficult and far from taking into account all their specificities. These shortcomings motivate the work presented base on recently introduced model-free control (MFC) concept. Indeed, faced with the hardship of modeling all the components of the meshed and complex supply chain systems, non-model-based control and particularly, the MFC law seems to be a sturdy alternative to deal with perishable inventory control. A preliminary study of inventory management problem of multi-product perishables, multi-echelon demand networks with perishability using MFC was started in [37]. Here, in order to achieve excellent delay compensation, considerable net stock reduction and attenuation of bullwhip effect that imply reduction of cost, an adaptive model-free control (AMFC) is developed for a robust and efficient control for supply chains with perishability. This dynamic inventory management approach is enhanced by a new prediction method for forecasting customer's demand. The paper is structured as follow. Section II reminds summarily the main basis of model-free control and its related intelligent controllers. Instead of Smith's predictors which are often used to compensate the system's delays and in order to anticipate the customer's demands, section III describes the forecasting tool, based on the new advances in times-series, that efficiently replaces it. Section IV presents for simulation purposes the used mathematical model of supply chain of perishable products. Several convincing computer simulations for a case study of foods supply chain, are discussed and analyzed both qualitatively and quantitatively in Section V. Finally, section VI gives some observations and outlook for future research.

## II. SHORT OVERVIEW OF MODEL FREE CONTROL

Since its introduction by M. Fliess and C. Join, [16], (See e.g. [18] for a detailed presentation), the indisputable practical successes of model-free control explains why it has already been summarized recently many times: [1], [3], [18], [15], [19], [28], [29], [35], [36]. This leads us to present only the general scheme and the main equations.

Briefly, the complex mathematical model of the studied system can always be replaced by the so-called ultra-local model given in the case of a first order system by

$$\dot{y}(t) = F(t) + \alpha u(t) \quad (1)$$

where,  $y(t)$ ,  $u(t)$  are the system's output and control variable, respectively.  $\alpha \in \mathbb{R}$  is a parameter often chosen by the practitioner.  $F(t)$  subsumes not only the unmodeled dynamics, but also all the unknown disturbances. It is estimated at any sample time by algebraic techniques as developed in [18], which leads to:

$$\hat{F}(t) = -\frac{6}{\tau^3} \int_{t-\tau}^t ((\tau - 2\sigma)y(\sigma) + \alpha\sigma(\tau - \sigma)u(\sigma)) d\sigma \quad (2)$$

where  $\tau$  is quite small and depends on the sampling period as well as the noise intensity. Closing the loop with the

following intelligent controller

$$u(t) = \frac{1}{\alpha} (-\hat{F}(t) + y^*(t) + C(e(t))) \quad (3)$$

where,  $y^*$  is the reference trajectory, and  $e(t) = y^*(t) - y(t)$ , the tracking error.  $C(e(t))$  stands for the classic controller

$$C(e(t)) = K_P e(t) + K_I \int e(t) + K_D \frac{de(t)}{dt} \quad (4)$$

Where  $K_P$ ,  $K_I$  and  $K_D$  are tuning gains. Figure 2, resumes the main principles of MFC.

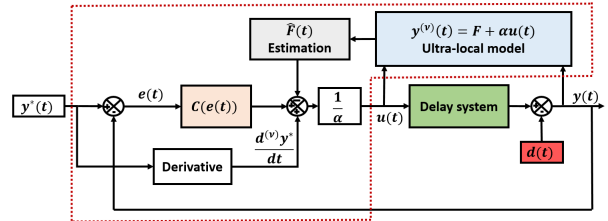


Fig. 2. General model-free control principle

## III. DELAY COMPENSATION AND DEMAND'S FORECASTING

Let us emphasize that as a typical example of time delay systems, the control of supply chains needs a delay compensation, Smith predictor [42], [43], which is a basic for controlling such systems were already employed a few times for supply chain management [9], [12], [11]. Usually, the use of Smith predictor assumes the knowledge of the delay, which is often unknown. To overcome this issue, instead of Smith predictor, the developed MFC approach is enriched by forecasting methods stemming from the new advances in time series as already used in [2], [33]. The new setting of time series, borrowed from [17], allows an easy forecasting of all the needed system's parameters. Let us emphasize that according to [17], the following presentation is quite a lot different from the existing methods, were other time series techniques are used (See e.g. [7]).

### A. Time series

Consider, as already defined in [17], a time interval  $[0, 1] \subset \mathbb{R}$  and introduce as usually in nonstandard analysis [10], [34], [39] the infinitesimal sampling  $\mathcal{I} = \{0 = t_0 < t_1 < \dots < t_v = 1\}$  i.e., "very small." A time series  $X(t)$  is defined as a function  $X : \mathcal{I} \rightarrow \mathbb{R}$ .

A time series  $\mathfrak{X} : \mathcal{I} \rightarrow \mathbb{R}$  is said to be quickly fluctuating, or oscillating, if, and only if, the integral  $\int \mathfrak{X} dm$  is infinitesimal, i.e., very small, for any appreciable interval, i.e., an interval which is neither very small nor very large.

According to a theorem due to Cartier and Perrin [8] (a theory of integration over finite spaces), the following additive decomposition holds for any time series  $X$ , which satisfies a weak integrability condition,

$$X(t) = E(X)(t) + X_{\text{fluctuation}}(t) \quad (5)$$

where,  $E(X)(t)$  is the mean, or trend which is "quite smooth", and  $X_{\text{fluctuation}}(t)$  is quickly fluctuating. The decomposition (5) is unique up to an infinitesimal.

## B. Forecasting via time series

The principle of forecasting of  $E(X)(t)$ , follows the parameters estimation of the first degree polynomial time function  $p_1(\tau) = a_0 + a_1\tau$ ,  $\tau \geq 0$ ,  $a_0, a_1 \in \mathbb{R}$ . Indeed, rewrite this function in operational domain (Laplace transform):

$$P_1 = \frac{a_0}{s} + \frac{a_1}{s^2} \quad (6)$$

Multiply both sides by  $s^2$ :

$$s^2 P_1 = a_0 s + a_1 \quad (7)$$

Take the derivative of both sides with respect to  $s$ , which corresponds in the time domain to the multiplication by  $-t$ :

$$a_0 = 2sP_1(s) + s^2 \frac{dP_1}{ds} \quad (8)$$

The coefficients  $a_0$  and  $a_1$  are achieved via the triangular system of equations (7)-(8). We get rid of the time derivatives, i.e., of  $sP_1$ ,  $s^2P_1$ , and  $s^2 \frac{dP_1}{ds}$ , by multiplying both sides of Equations (7)-(8) by  $s^{-n}$ ,  $n \geq 2$ . We obtain, in time domain a set of iterated integrals which corresponds to low pass filters allowing to attenuate the corrupting noises. Notice that a quite short window is needed to obtain accurate values of  $a_0$  and  $a_1$ .

The estimation of  $a_0$  yields the mean  $E(X)(t)$ , in (5). The extension to polynomial functions of higher degree is straightforward. For derivative estimates up to some finite order of a given smooth function  $f: [0, +\infty) \rightarrow \mathbb{R}$ , take a suitable truncated Taylor expansion around a given time instant  $t_0$ , and apply the previous computations. Resetting and utilizing sliding time windows permit to estimate derivatives of various orders at any sampled time instant.

Set the following forecast  $X_{forecast}(t + \Delta T)$ , where  $\Delta T > 0$  is not too "large".

$$X_{forecast}(t + \Delta T) = E(X)(t) + \left[ \frac{dE(X)(t)}{dt} \right]_e \Delta T \quad (9)$$

where  $E(X)$  the mean which we predict is estimated like  $a_0$  and  $\left[ \frac{dE(X)(t)}{dt} \right]_e$  as  $a_1$ .

## C. Adaptive model-free control

1) *Principle*: Take the system (1) with a delay  $\theta$  and apply the Smith predictor [42]:

$$\hat{y}(t + \theta) = \hat{F}(t + \theta) + \alpha u(t) \quad (10)$$

where  $\hat{y}(t + \theta)$  and  $\hat{F}(t + \theta)$  are the estimate and the forecast of  $y(t)$  and  $F(t)$ , respectively. The corresponding iP controller reads

$$u_{amfc}(t) = \frac{1}{\alpha} (-\hat{F}(t + \theta) + \hat{y}^*(t + \theta) + K_P \hat{e}(t + \theta)) \quad (11)$$

where  $\hat{e}(t + \theta) = \hat{y}^*(t + \theta) - \hat{y}(t + \theta)$  is the estimation of the tracking error at time  $(t + \theta)$ . In order to estimate  $\hat{y}(t + \theta)$ , integrate Equation (10)

$$\hat{y}(t + \theta) = \int \hat{F}(t + \theta) + \alpha u(t) \quad (12)$$

Notice that the estimation of  $\hat{y}(t + \theta)$  needs the forecast  $\hat{F}(t + \theta)$  of  $F$ . The main tool which is used here rests on the new trend in time series presented above<sup>2</sup>.

*Remark 3.1*: Tools from algebraic methods are used in the case of unknown delay  $\theta$ .

2) *Forecasting  $\hat{F}(t + \theta)$* : According to Section III-B, the forecast  $\hat{F}(t + \theta)$  of  $F$  is obtained like  $a_0$ .

$$e^{-\theta s} \hat{F}(s) = 2sF(s) + s^2 \frac{dF(s)}{ds}$$

Multiply both sides of the above equation by  $s^{-3}$  and rewrite it in the time domain using Cauchy formula leads

$$\hat{F}(t + \theta) = \frac{2 \left[ \int_{t_0}^t (2t - 3\tau) F(\tau) d\tau \right]}{t^2} \quad (13)$$

Using all the components above, the general scheme of the proposed approach so called Adaptive Model-Free Control, (AMFC) is summarized in Fig. 3. The desired behavior is obtained thanks to the primary controller stemming from Model-Free Control (3)-(4) with ( $K_I = K_D = 0$ ) and the delay compensation via forecasting.

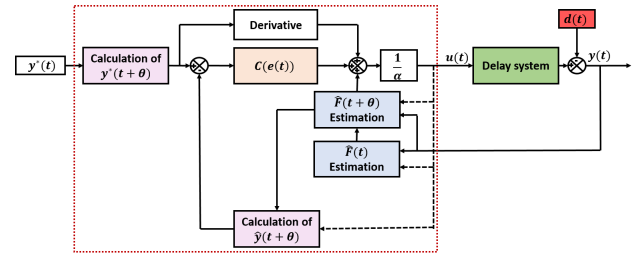


Fig. 3. Adaptive Model-Free Control (AMFC)

## IV. SUPPLY CHAIN DYNAMIC MODEL AND CONTROL

The used for simulation purposes model, is built in order to reflect the system dynamics governed by the proposed approach, i.e, adaptive model-free Control (AMFC) with customer's demand forecasting and compared to basic MFC. The goal is to evaluate the system's behavior over the planning horizon and build outputs that will serve to compute the profit, total cost, customer satisfaction and bullwhip effect used for quantitative studies.

### A. Mathematical modeling of production-inventory system

The considered system is a production system composed of a distribution center warehouse and a supplying unit. A supplying unit is characterized by a non-negligible lead time (delay) noted by  $\theta$ , supposed to be constant which corresponds to the time required for taking the decision to produce the goods until delivering the goods to the storage unit and by order rate (or production rate) or the input of the system denoted  $u(t)$  presents the order to produce and deliver the flow of products, which is limited by a maximum supplying order rate denoted  $u_{max}$  and a storage unit that is

<sup>2</sup>The same approach is very useful and it is used for customer's demand forecasting in this paper.

characterized by the outgoing flow of products leaving the system due to the customers demand  $d(t)$ , sales made and the incoming flow of products.

The on-hand stock  $y(t)$  in the planning horizon  $T_f = N * T_s$  ( $T_s$  is the sampling time) used to fulfill the market demand  $d(t)$  deteriorates at a constant rate  $\sigma$ ,  $0 \leq \sigma < 1$ . The stock balance equation reads,

$$\frac{dy}{dt} = \begin{cases} -\sigma y(t) - d(t), & 0 \leq t < \theta \\ -\sigma y(t) + \rho u_r(t) - d(t), & t \geq \theta \end{cases} \quad (14)$$

where  $\theta$  is the factory throughput time,  $u_r(t) = u(t - \theta)$  is the received shipment and  $\rho$  ( $0 \leq \rho \leq 1$ ) is the yield.

### B. Constraints and objectives

Physical limitations like the flow rates  $u(t)$ , the market demand  $d(t)$  and inventory level  $y(t)$  can take only non-negative values, so the controller design should take into account these positive and saturation constraints that are formulated as follows:

$$\begin{cases} u_{min} \leq u(t) \leq u_{max} \\ d_{min} \leq d(t) \leq d_{max} \\ y_{min} \leq y(t) \leq y_{max} \end{cases} \quad (15)$$

Let us emphasize that both the AMFC and MFC do not require any mathematical model of the studied supply chain system.

## V. SIMULATION: THE CASE OF PERISHABLE PRODUCTS

### A. Problem description

The control objective is to keep the inventory level  $y(t)$  at its desired pre-specified value  $y^* = 10000$  MT (Mega tonnes) of goods. Customer's demand depicted in Fig. 4 presents several uncertainties, and must be satisfied respecting constraints given by (15).

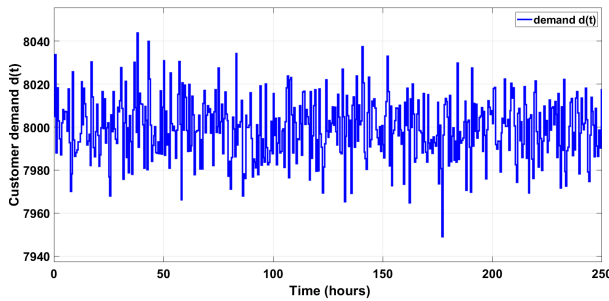


Fig. 4. Customers demand of the perishable product

The stochastic demand is bounded  $d_{min} \leq d \leq d_{max}$  with  $d_{min} = 0$  and  $d_{max} = 8500$  MT/h. Assume that  $\theta = 2$  h and  $\sigma = 0.9$  while  $\rho = 1$ . In addition and in order to conduct quantitative analysis, all used variables and formulas are summarized in Table I.

### B. Numerical results

The conducted extensive simulations provide us a basic for both qualitative (robustness of the control algorithms) and quantitative analysis

TABLE I  
DEFINITIONS OF VARIABLE AND NOTATION.

Variables	Symbol description
$\lambda_R$ (\$)	The price of an item
$\lambda_C$ (\$)	Cost of producing an item
$\lambda_I$ (\$)	Storage cost per item
$R = \sum_{t=0}^{T_f} \lambda_R d(t)$	Revenue
$PC = \sum_{t=0}^{T_f} \lambda_C d(t)$	Production cost
$IC = \sum_{t=0}^{T_f} \lambda_I y(t)$	Inventory storage cost
$TC = PC + IC$	Total cost
Profit = $R - PC - IC$	Profit
Bullwhip = $\frac{Var_{out}/\mu_{out}}{Var_{in}/\mu_{in}}$	Bullwhip effect
Var, $\mu$	Variance and mean
$z(t) = \rho u(t) - \sigma y(t)$	variable flow
$w(t) = d(t) + y(t)$	variable flow
$CS = \left[ 1 - \sum_{t=0}^{T_f} \left( \frac{d(t) - z(t)}{d(t)} \right) \right] \times 100$	Customer satisfaction
$MTE = \frac{1}{N} \sum_{i=1}^N  y_{d,i} - y_i $	Mean Tracking Error (MTE)

1) *Qualitative analysis:* Fig. 5, shows the inventories levels  $y(t)$  obtained using MFC and AMFC with customer's demand forecasting and their corresponding production rates depicted in Fig. 6.

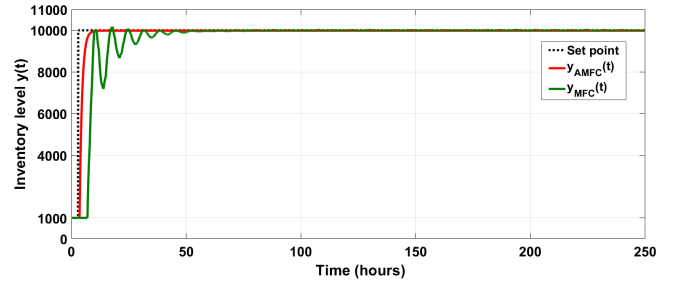


Fig. 5. Inventory level  $y(t)$  with AMFC and MFC

The AMFC reacts faster to the changes in market conditions than MFC. The two controllers converge to the desired value  $y_d = 10000$  (MT) and one can noticed, the AMFC stands out from MFC in terms of qualitative performance (rise time (RT), settling time (ST), overshoot(OV)) and robustness (Mean Tracking Error) against the delay and the uncertainty of demand summarized in Table II

TABLE II  
PERFORMANCES OF AMFC AND MFC

Policies	RT (h)	ST (h)	OV	$ U_{max} $	TCS (h)	MTE
AMFC	2.2329	7.722	0	17000	8	78.19
MFC	2.3519	42.225	10173	18457	38	276.02

The smoothening observed in the net stock  $y_{AMFC}(t)$  and the production rate  $u_{AMFC}(t)$  obtained by AMFC compared to fluctuations observed in the case of MFC alone, is due to the fact that AMFC anticipate the customers demand before its occurs using forecasting and compensate the delay  $\theta$ . In addition, the maximal value of factory starts  $u(t)$  is also considerably reduced see Fig. 6, and  $|U_{max}|$  in Table II .



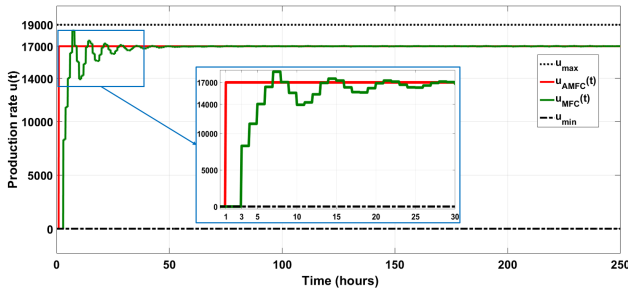


Fig. 6. Production rate  $u(t)$  with AMFC and MFC

Fig. 7 represents the customer satisfaction  $CS(t)$  with AMFC and MFC obtained as mentioned in Table I.

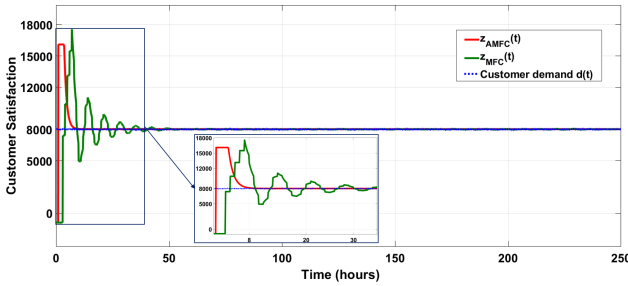


Fig. 7. Customer satisfaction  $CS(t)$  with AMFC and MFC

The  $CS$  is evaluated by comparing the rate of arrival of orders from the customers with the rate of deliveries to them and it provides information on the ability of the system to deliver orders on time. Fig. 7 and the value of Time of Customer Satisfaction (TCS) in Table II show that orders with AMFC are satisfied after around  $t \approx 8$ h against  $t \approx 38$ h with MFC.

2) *Quantitative analysis*: The quantitative analysis based on the information provided by Tables I, III and IV. Table III shows the performance of the control policies in terms of storage costs, and production costs, total costs, and Table IV presents the average customer satisfaction, the bullwhip effect and profit with AMFC and MFC compared to ideal case (noted here, base 0) and the errors (extra/least) are reported in a percentage.

TABLE III  
COST VALUE AGAINST AMFC AND MFC

Policies	Total Cost		Storage Cost		Production Cost	
	( $10^8$ \$)	(%)	( $10^6$ \$)	(%)	( $10^8$ \$)	(%)
Base 0	2.0257	ref	2.474	ref	2.0010	ref
AMFC	2.0502	+1.2105	2.4544	-0.7905	2.0257	+1.24
MFC	2.0927	+3.3082	2.4067	-2.7203	2.0687	+3.38

Using the AMFC control policy, the system achieves high customer service levels. These achievements imply that the system is able to dampen completely the inventory oscillations, and the customer satisfaction levels drop on average to 98.76% and by using MFC, the system achieves the highest the customer satisfaction level drops up to 99.98% . The

effect of the control policies influences over the total costs of the system.

When using the AMFC, production cost increase by +1.24% against the ideal case, whereas by using MFC, the increase goes up by +3.38% and something similar happens in the total costs. But their storage costs are reduced at least by  $-0.79\%$  for AMFC and  $-2.72\%$  for MFC. Then the profit obtained by AMFC is higher by  $\Delta Profit = 4.2493 \times 10^6$ \$ than MFC.

TABLE IV  
COSTUMER SATISFACTION WITH AMFC AND MFC

Policies	Customer Satisfaction (%)		Bullwhip Effect		Profit ( $10^8$ \$) (%)	
		$d(t) = z(t)$		$u(t) = w(t)$		
Base 0	100	$d(t) = z(t)$	1	$u(t) = w(t)$	5.978	ref
AMFC	98.76	-1.2378	1.26	+0.26	5.9537	-0.41
MFC	99.98	-0.0176	1.66	+0.66	5.9112	-1.12

The amount of orders that arrives to the next level is amplified and the next level receives more orders than the actual orders placed to the system, this phenomena is called bullwhip effect. The objective is to use the control policies to dampen down or to eliminate the fluctuations in the demand orders to the next level. In table IV and Fig. 6, it is clear that controllers are not able to cancel the amplification problem however AMFC show a lower magnitude, so it does a better job in dampening down the amplification, which reduces the arrival of misleading demands to the manufacturing site.

## VI. CONCLUSION

Considering the strong constraints to which the supply chains of perishable products are subjected and by taking into account the major difficulties in writing down a reliable mathematical model for their description, this paper provides an easy yet efficient policies to deal with the tactical inventory dynamic management. The proposed approaches rest on the use of both MFC and AMFC where the use of any mathematical model becomes useless. Instead of the use of Smith predictor, the paper introduces the application of the advances in time series to handle the problem of delay. In addition, and in order to solve the problem of the continuous overshoots at the output inventory level in response to abrupt demand changes, which leads to the increased storage space, the proposed approach is enhanced by the introduction of the algebraic methods to perform customer's demand forecasting. The obtained convincing results shows the ability of AMFC to deal with the various constraints encountered in supply chains of perishable products and exhibit excellent results both qualitatively and quantitatively. Further works consider the application of the approach to more complex supply chains with the estimation of the different delays encountered in the various nodes of the system.

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