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An Efficient Framework for Tactical Management in Supply Chain Systems

Danielle Nyakam Nya and Hassane Abouaïssa

Univ. Artois UR 3926, Laboratoire de Génie Informatique
et d'Automatique de l'Artois (LGI2A) F-62400 Béthune, France
`(danielle.nyakamnya,hassane.abouaissa)@univ-artois.fr`

***Abstact*— Although dynamic supply chain management is nowadays quite widely studied, several problems related to their control remain a challenging task. Indeed, most of the methods are model-based control strategies where supply chain models play a major role. The increasing complexity of these systems makes their representation more difficult and fails to capture all the dynamic behavior of the supply chain networks. This paper proposes a new efficient and easy implementable framework for tactical management in supply chain systems. The developed approach rests on the use of model-free control in order to deal with the inventory control of supply chains. The provided numerical simulations of a petrochemical example shows the effectiveness and robustness of model-free controllers against the classic controllers.**

***Keywords*—**Supply chain management; model-free control; inventory control; intelligent controllers.

I. INTRODUCTION

The study and control of supply chains have arisen interest on the research community and enterprises because of implicit economic benefits [1]. The excellent reviews provided in [2], [3], [4], [5], [6] permit to underline the importance of automatic theory methods in the management of the different processes in the supply chain systems. Successfully control algorithms have been then developed. The classical PID controllers was presented in [7] and applied by [8] in order to control the inventory level in supply chain at a desired values, considered as the optimal one aiming to satisfies the market demand timely and most effective way and to synchronize the incoming and outgoing flows of each supply chain component. [9], [10] have proposed the application of the differential flatness concept which seems to be more efficient for complex and highly nonlinear systems. Dynamic programming and optimal control methods aims to optimize an objective function that describes the performance of the system were applied by [11] and [12]. This standard procedure allows to obtain an optimal state feedback control [2]. Early in 1999, [13] has proposed a PID like controller for the management of inventory levels in supply chains.
Robust control theory allows to take into account uncertainties concerning customer demand, machine failure and lead times as shown in [14], [15], [16]. In this framework, uncertainties are unknown but bounded quantities and constraints dictated by specifications and physical limitations [2]. More realistic and optimal results call for the introduction of forecasting techniques in order to capture the changing demand and uncertainties in the market in supply chain planing to maintain an inventory level in order to satisfy the customer demand. As depicted in the works of [17], [18], [19], model predictive control (MPC) has been applied to solve a dynamic optimization problem of the inventory. In [20], MPC control is used to demonstrate that safety stock levels can be significantly reduced and financial benefits achieved while maintaining satisfactory operating performance in supply chain. Concret applications of MPC and Internal Model Control (IMC) have been developed in [21], [22], [23].

It is important to underline that most of the developed control strategies are model-based where supply chain models play an important role. The increasing complexity of these systems makes their representation more difficult and fails to capture all the dynamic behavior of the supply chain networks. As stated in [24], writing a "*good model*", where constraints and perturbations might be severe, is quite beyond our reach especially if online calibration ought to be performed. In addition, the use of more or less a good model, needs the identification of several parameters to assess a particular control strategy which is also true in the supply chain systems [26]. In this framework, a new setting of "*model-free control*" (**MFC**) and its corresponding intelligent controllers seems to be an efficient solution to tackle the problem in a new control-oriented tactical decision policy for inventory management in a production-inventory system and supply chain management area that permits to answer, from our point of view, to the addressed problem. Such control strategy which avoids the use of any mathematical model of the studied supply chain, allows easily to take into account the inherent perturbations. In addition, its corresponding intelligent controllers are easy to tuned and to implement (See, e.g., [24], [25], for an in-depth presentation of model-free control and the meaning of intelligent controllers). Since it introduction in the field of automatic control, MFC already had many successful concrete applications (See e.g., [27], [28], [29] [30], [31], [32], [33], [34], [35] and the references therein).

This paper deals with the operational activities of supply chain dynamics and propose an efficient framework for tactical management in supply chain. The developed approach rests on the use of an Intelligent control algorithm, stemming from model-free control theory, which allows the regulation of inventory levels while ensuring a synchronization of the flow at the whole supply chain. A first attempts has already presented in [36] and [37]. The jointly use of MFC and Smith predictors has been developed in [38]. Here, the application of MFC is oriented towards a linear supply chain with application to a petrochemical problem stemming from [8]

The organization of the paper is as follow. Section II, describes the used model for the studied supply chain system. Section III, recalls the main principles of model-free control and its corresponding intelligent controllers. Simulation results of the proposed algorithm to linear supply chain, and analysis are provided in Section IV. Some concluded remarks and future works are reported in Section V.

II. MATERIAL FLOW RATE MODEL FOR SUPPLY CHAINS

Several approaches stemming from traffic theory are used to deal with supply chain modeling and analysis. It is important to stress that several phenomena like transport and production, lead to unavoidable lead times or throughput times. Therefore, delay differential equations play a key role.

Following [39], a supply chain model can be modeled with analogy with traffic flow theory. Then, the set of elements of supply chains can modeled using linear differential equation. In order to understand the dynamic behavior of Supply Chain consider the following example of sequential chain (Fig. 1).

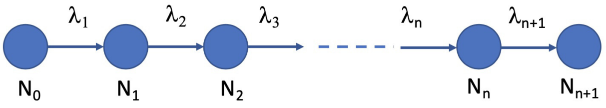

Fig. 1: Linear supply chain

Models of supply chain systems are based on a set of nodes (represented by circles) which represent the suppliers i, characterized by an inventory level N_i, $(i = 1, \dots n)$. The production or incoming rate λ_i, depending if the node is producer (manufacturing cell, for exemple) or non-producer (warehouse, supplier or distribution center, ...). This parameter could represent the production speed of this supplier. $i = 0$, corresponds to a resource center that provides raw materials and $i = n+1$, is the final customer.

According to [8], the producer node is characterized by a variation of its production rate by varying its internal production policy. It is important to underline that the models either for a non producer or producer nodes, as provided by [8], fail to take into account explicitly the intrinsic parameter of delay. For this, a relatively modified model tacking into account this delay is introduced in both producer and non producer nodes.

A. Non producer node model

Equation (1), describes the dynamic change in inventory level as a difference between the production or incoming rate λ_i and the delivery flow rate y_i.

$$\dot{N}_i(t) = \gamma \lambda_i(t-\theta) - y_i(t), \qquad t \geqslant \theta \tag{1}$$

where, the delivery flow rate $y_i(t)$ corresponds to the customer total demand.

$$y_i(t) = \sum_{j=1}^{r} F_{i,j} \lambda_j(t) \tag{2}$$

The output $N_i(t) \geqslant 0$ is the inventory level, and $\lambda_i(t) \geqslant 0$ represents the control variable. The adaptation time θ is assumed to be known. $F_{i,j}$ represents the stoichiometric ratio of the stock product in node i that is required by node j, (See e.g., [8]). Finally, γ is a yield parameter which might be poorly known.

In [38], the authors have provided a mathematical illustration of the so-called *bullwhip effect*. Indeed, if the desired inventory level either for production or non production node, is assumed to be constant i.e., $\dot{N}_i(t) = 0$, then (1) yields $\lambda_i(t) = \frac{y_i(t+\theta)}{\gamma}$. In this case, the individual demand has to be “guessed”. In addition, no theoretical technique will ever produce rigorously accurate predictions. For simplicity’s sake let us presume here a constant bias $b \neq 0$, i.e., $\dot{N}_i(t) = \frac{b}{\gamma}$. Thus, $N_i(t) = \frac{b-\theta}{\gamma}(t-\theta) + N_i(\theta)$, $t \geqslant \tau$. Its absolute value $|N_i(t)|$ becomes very large, at least from a purely mathematical standpoint, when $t \longrightarrow +\infty$. Notice that, although the bullwhip effect phenomenon is more or less understood, the literature does not seem to contain any clear-cut definition of this effect.

B. Producer node model

The incoming rate varies accordingly to production policies and process dynamical behavior. Change in the production rate involves several activities that require a delay time θ which appears in (1). Then its dynamics can be represented by:

$$\dot{\lambda}_i(t) = \frac{1}{T_i}\left[W_i(t) - \lambda_i(t)\right] \tag{3}$$

where, $W_i(t)$ represents the control variable that varies the production rate λ_i, in a producer node, in contrast with a non producer node, where λ_i corresponds only to the materials that are received from its suppliers. T_i is the adaptation time of the production rate λ_i. Equations (1) and (3) give the dynamic model of producer node.

The main objective of the designed controller for such systems is to keep inventory levels at a desired value by regulating the production or incoming rate. Either for a producer or non producer node the inventory level N_i are to be controlled indirectly through λ_i.

Physical limitations (bounds in the inventory levels $N_i(t)$ and flow rates λ_i for a non-producer node and W_i for a producer node must be taking into account as follow:

$$\begin{cases} N_{i,min} \leq N_i \leq N_{i,max} \\ 0 \leq \lambda_i \leq \lambda_{i,max} \\ 0 \leq W_i \leq \lambda_{i,max} \end{cases} \tag{4}$$

Although the above models describe more or less the behavior of the system, the proposed model-free controller ignores these descriptions since its rests on an ultra-local model which is continuously updated. The following section recalls the principle of this paradigm.

III. MODEL-FREE CONTROL: AN OVERVIEW

Model-free control is defined as an original concept based on the algebraic estimation and it is independent of any precise mathematical model of the system to be controlled. Since the first work of [24] several concret and successful applications around the world has be developed in most diverse fields as intelligent transportation systems [31], [35], [33], robotic [32], energy management [30], ...

Consider the input/output model of the system (5), that can be nonlinear in most cases and unknown or as stated in [34], at least poorly known.

$$E\left(y, \dot{y}, \ldots, y^{(a)}, u, \dot{u}, \ldots, u^{(b)}\right) = 0 \tag{5}$$

Following the principle of MFC, the system described by (5) is replaced by the so-called "*ultra-local (or phenomenological) model*":

$$\boxed{y^{(\nu)} = F + \alpha u} \tag{6}$$

where:

- $y^{(\nu)}$ is the derivative of order $\nu \geqslant 1$ of y. The integer ν is selected by the practitioner. Several concert examples and applications show that ν may be chosen quit low, i.e., 1, or only seldom, 2.
- $\alpha \in \mathbb{R}$ is a non-physical constant parameter. It is chosen by the practitioner such that αu and y^{ν} are of the same magnitude.
- F, which is continuously updated, subsumes the poorly known parts of the plant as well as of the various possible disturbances, without the need to make any distinction between them.

A. Intelligent controllers

Assume that F is estimated and close the loop with the intelligent PID (*iPID*) controller,

$$u = -\frac{F_{est}(t) - y_{ref}^{(\nu)}(t) + C(e(t))}{\alpha} \tag{7}$$

where

- y_{ref} is the reference trajectory,
- $e = y - y_{ref}$ is the tracking error,
- F_{est} is an estimate value of F,
- $C(e(t)) = K_P e(t) + K_I \int e(t) + K_D \frac{de(t)}{dt}$,
- K_P, K_I and K_D are the usual tuning gains.

Equations (6) and (7) yield

$$\ddot{e} + K_D \dot{e} + K_P e + K_I \int e = 0 \tag{8}$$

In (8), F does not appear anymore, which means that the unknown parts and disturbances of the system vanish. We are therefore left with a linear differential equation with constant coefficients of order 3.

The tuning of K_P, K_I and K_D becomes therefore straightforward for obtaining a "good" tracking of y_{ref}. This is a major benefit when compared to the tuning of of "classic" PIDs, (See, e.g., [24], for a complet description of MFC concept),

B. Online estimation of F

Assume that $\nu = 1$ in (6). In Laplace domain it becomes

$$sY = \frac{\Phi}{s} + \alpha U + y_0 \tag{9}$$

where

- Φ is a constant,
- y_0 is the initial condition corresponding to the time interval $[t-\tau, t]$.

In order to get rid of y_0, multiply both sides by $\frac{d}{ds}$

$$Y + s\frac{dY}{ds} = -\frac{\Phi}{s^2} + \alpha \frac{dU}{ds} \tag{10}$$

For smoothing the noise, multiply both sides by s^{-3} which in time domain yields[1].

$$F = -\frac{6}{\tau^3} \int_{t-\tau}^{t} ((\tau - 2\sigma) y(\sigma) + \alpha \sigma (\tau - \sigma) u(\sigma)) d\sigma \tag{11}$$

where σ is quite small and depends on the sampling period as well as the noise intensity.

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[1] According to the equivalence: $s^{-n} \to \int^{(n)}$, (11) corresponds to the multiple integrals which are easily implemented as discrete linear filters.

IV. SIMULATION RESULTS: APPLICATION TO A PETROCHEMICAL PLANT

The conducted simulation study concerns the linear model of a petrochemical multi-product plant borrowed from [8], (See Fig.2).

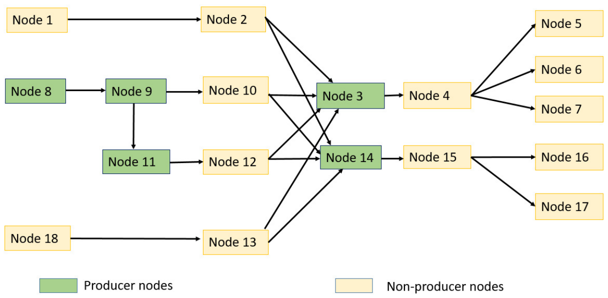

Fig. 2: Representation of the petrochemical plant

The number on the nodes identifies the numbering used through the simulations and figures presenting plots of the results. Hexane and catalyst are imported, whereas ethylene is obtained from a local refinery. The production of ethylene and butane is carried out by independent production plants (producer nodes). There exist intermediate storages for hexane, ethylene, butane and catalyst feedstocks (non producer nodes). Only five demand sources are taken into consideration from D_1 to D_5 (Nodes 5, 6, 7, 16 and 17).

The following table 1, stemming from [8] resumes the nomenclature for each node of the studied petrochemical plant.

TABLE 1: Node nomenclature

node	element	node	element
1	hexene ship	2	hexene store
3	reactor R_1	4	store A_1, A_2
5,6,7	client D_1, D_2, D_3	8	refinery
9	ethylene plant	10	ethylene store
11	butene plant	12	butene store
13	catalyst store	14	reactor R_2
15	store B_1, B_2	16,17	client D_4, D_5
18	Catalyst		

A. *Model-free control of a non producer node*

The studied petrochemical plant is composed of the following non producer nodes:

$C_{n-p} = \{1,2,4,5,6,7,10,12,13,15,16,17,18\}$. Following Section III, each node can be described by the following phenomenological model:

$$\dot{N}_i(t) = F_i(t) + \alpha_i u_i(t) \tag{12}$$

where $u_i = \lambda_i$ represents the control variable allowing to maintain the level at a desired positive value. F_i is estimated as above.

Consider as illustrative example the control of the level in the non producer node $i = 4$.

$$\dot{N}_4(t) = F_4 + \alpha_4 u_4(t) \tag{13}$$

The corresponding control $u_4 = \lambda_4$ is obtained immediately

$$u_4(t) = -\frac{1}{\alpha_4}\left[[F_4]_{est} + N_{4,ref} + K_{P4}e(t)\right] \tag{14}$$

where

- $e(t) = N_4(t) - N_{4,ref}$ represents the tracking error.
- K_{P4} is a tuning gain[2].

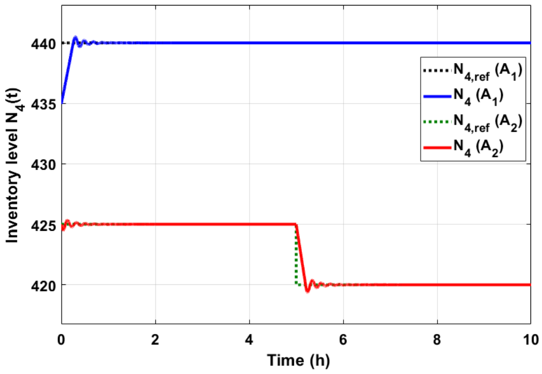

Fig. 3: Time evolution of the inventory level N_4

At this node, Reactors R_1 and R_2 change from producing product A_1 to A_2 and B_2 to B_1 at the half of time of simulation. Excellent results are obtained despite the sudden change in the desired level (See. Fig.3)[3].

The results in Fig. 4 show the time evolution of the level for the non producer node N_{15} which is storage node for B_1 and B_2.

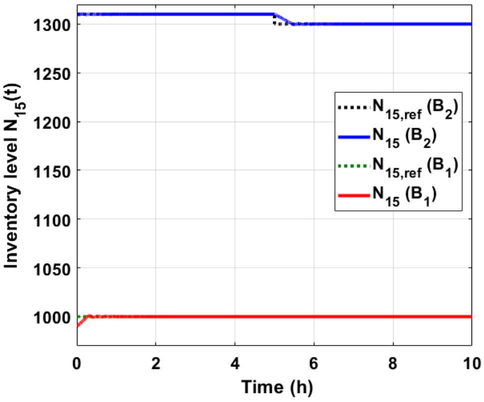

Fig. 4: Time evolution of the inventory level N_{15}

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[2] The linear character of the studied system shows that the use of an i-P is sufficient to deal with the control of the level. The integral part of the controller is already included in the estimation of F.

[3] See e.g., [8], or the different values of production rations as well as initiale conditions values.

As depicted in these figures, the proposed controllers show high efficiency against uncertainties and demonstrate how the desired values of each level in the studied supply chain are reached. In the same time, it guarantees the synchronization of the flows at different levels of the studied plant (See Fig.5).

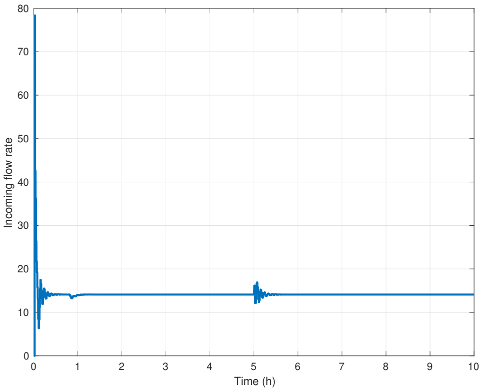

Fig. 5: Variation of the incoming flow rate λ_{15}

B. *Model-free control of a producer node*

In addition to the non producer nodes, the petrochemical plant contains a set of producer node: $C_p = \{3, 8, 9, 11, 14\}$ In the case of producer node, the control algorithm follows the same reasoning as in the non producer case. Then and Without a loss of generality, the obtained control, for each node reads:

$$W_i = -\frac{1}{\alpha_p}\left[[F_i]_{est} + \lambda_{i,ref} + K_{Pi}e(t)\right] \tag{15}$$

Figure 6 shows the time evolution of the level at the producer node N_9. Here also, the controller manages efficiently the different nodes to the desired values and permits to synchronize the whole system.

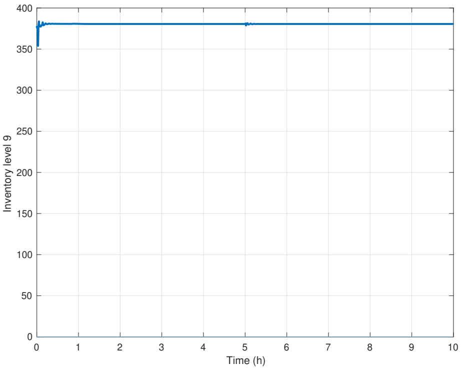

Fig. 6: Time evolution of the level of the producer node N_9

Figure 7 shows the incoming flow rate variation at the node N_{11}.

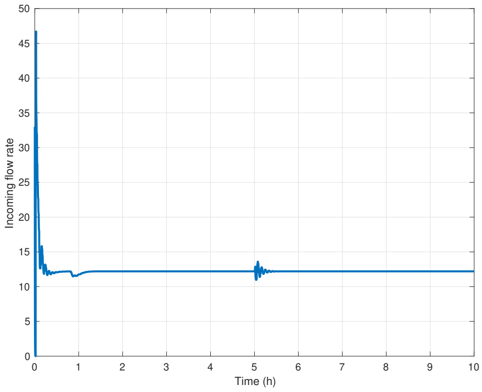

Fig. 7: Variation of the incoming flow rate λ_{11}

V. CONCLUSION

The model-based control of supply chain has been a subject of several studies and application and remain until today an open problem. Most of the proposed algorithms must faces the thorny problem of a realistic representation of the studied system. In addition, the control laws must also deal with uncertain customer demand as well as stochastic conditions.

In this paper, we focused on the development of an efficient framework for tactical management in supply chain systems, where the need for a mathematical model is no longer necessary. Simulations results show that a simple Intelligent proportional or iP controller seems to be more adapted to deal with such systems.

However, several further studies must be conducted in order to deal with the important issue of bullwhip effect and its attenuation. Critical supply chain systems which include perishable production must be deeply studied and controlled. Uncertainties of customer demands for example will be tacked into account by introducing a deterministic approach for demand forecasting. Several works as in [40] have demonstrated that the application of control theory approaches can easily reduce stock levels by up to 80% compared to 20-30% with MRP and hence reduce cost. These assessments must be demonstrated in the case of the proposed, in this paper, model-free control approach.

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