Predictive control of multi-source - multi-channel supply chain under the influence of self-media live broadcast

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Abstract. The proposed approach combines a multi-source- multi-channel supply chain system with Model Predictive Control (MPC), with a specific focus on the impact of self-media live streaming. The study begins by modeling and analyzing the multi-source-multi-channel closed-loop supply chain under the influence of self-media live streaming. Subsequently, the integration of MPC is explored, leveraging its predictive and rolling optimization capabilities to mitigate the bullwhip effect. To evaluate the effectiveness of the proposed approach, simulation analysis is conducted using Simulink. The experimental results confirm that the proposed method successfully mitigates the bullwhip effect, ensuring a dynamic system performance.

Keywords: Model predictive control; Self media live streaming; Multi-source - multi-channel; Closed-loop supply chain; Bullwhip effect

1 Introduction

The rise of 5G, AI has diversified the global shopping market with live-streaming e-commerce, significantly impacting traditional sales models [1]. This e-commerce form offers two shopping experiences: self-operated live-streaming and self-media live-streaming, utilizing dedicated warehouses [2]. Optimizing inventory control algorithms for self-media live-streaming becomes crucial as these e-commerce channels expand.

Existing research on closed-loop supply chains includes MPC algorithms for optimal inventory management [3]. Control theory methods maximize profits with improved decision strategies for recycling channels [4].Distributed and centralized MPC approaches address specific supply chain challenges [5-6], effectively mitigating the bullwhip effect and enhancing efficiency and stability.

In summary, existing supply chain research has mostly focused on dual-channel studies. This paper addresses inventory optimization in a multi-source, multi-channel closed-loop supply chain system, considering the impact of self-media live-streaming. The main objectives are: Firstly, establish a model for the system and derive inventory balance equations. Next, integrate the inventory balance equations with MPC for optimal control. Lastly, conduct MATLAB simulations to validate inventory, production/order quantities, and the bullwhip effect equilibrium.

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2 Modeling of a Multi-Source-Multi-Channel Closed-Loop Supply Chain

This paper proposes a multi-source-multi-channel closed-loop supply chain model (Figure 1) for the Chinese apparel industry. It includes four consumer access points: self-operated live-streaming, self-media live-streaming, traditional online, and traditional offline. The model covers both forward and reverse channels.

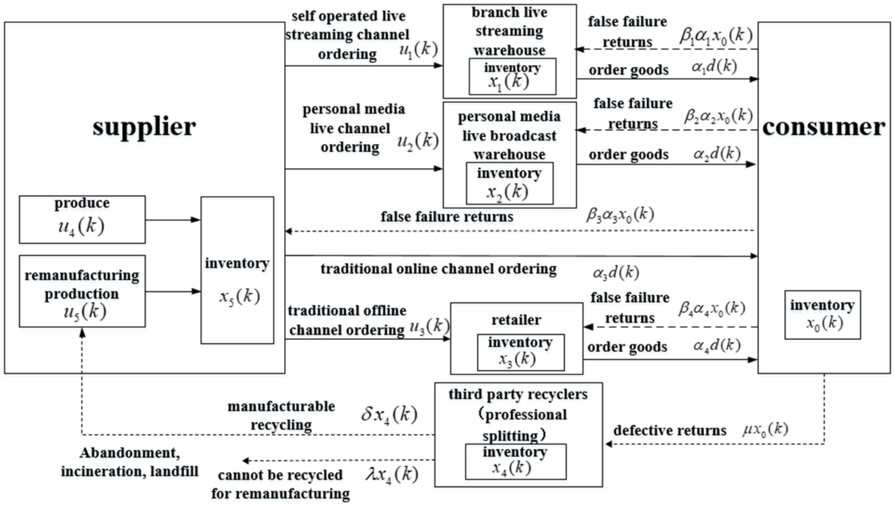

Fig. 1. closed-loop supply chain model with multiple sources multi source - multi channel

According to reference [7], the inventory balance equation is represented in matrix form as follows:

$$x(k+1) = \xi x(k) + \varphi u(k) \tag{1}$$

$$y(k) = \Psi x(k) \tag{2}$$

Where: $\xi = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & \beta_3\alpha_3 \\ 0 & 1-\delta-\lambda & 0 & 0 & 0 & \mu \\ 0 & 0 & 1 & 0 & 0 & \beta_4\alpha_4 \\ 0 & 0 & 0 & 1 & 0 & \beta_2\alpha_2 \\ 0 & 0 & 0 & 0 & 1 & \beta_1\alpha_1 \\ 0 & 0 & 0 & 0 & 0 & 1-\beta_1\alpha_1-\beta_2\alpha_2-\beta_3\alpha_3-\beta_4\alpha_4-\mu \end{pmatrix}$,

$\varphi = \begin{pmatrix} 1 & 1 & -1 & -1 & -1 & -\alpha_3 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & -\alpha_4 \\ 0 & 0 & 0 & 1 & 0 & -\alpha_2 \\ 0 & 0 & 0 & 0 & 1 & -\alpha_1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$, $\Psi = \begin{pmatrix} I \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}^T$

The equation includes variables "$x(k)$" for inventory levels, "$u(k)$"for production/order quantities, and "$y(k)$" for output inventory levels at each node at time "k".

Variable "$\beta_n(n = 1,2,3,4)$" represents the return rate in a defect-free market. The variable "$\alpha_m(m = 1,2,3,4)$" represents the market inclination rates for four channels: self-operated livestreaming, self-media livestreaming, traditional online, and traditional offline. It is essential to ensure that these rates comply with the condition "$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1(0 \leq \alpha_m \leq 1)$". Variable "$\mu$" represents the defective return rate of goods, variable "δ" represents the remanufacturing rate of goods, and variable "λ" represents the discard rate of goods.

3 Design of the model predictive control algorithm

3.1 Design of the predictive model

Based on the historical information of the controlled object at time "k", within the control time domain "m", the system's state and output at time "$k + 1$" are computed using equations (1) and (2) as the prediction model. By forecasting the future state and output of the system within the time domain "$p(m \leq p)$", the prediction model can be represented in the following matrix form:

$$\begin{cases} \hat{X}(k) = \xi_x x(k) + \varphi_x U(k) \\ \hat{Y}(k) = \Psi_y x(k) + \Theta_y U(k) \end{cases} \tag{3}$$

where, $\hat{X}(k) = \begin{bmatrix} X(k+1) \\ \vdots \\ X(k+p) \end{bmatrix}_{(np\times 1)}$, $\xi_x = \begin{bmatrix} \xi \\ \vdots \\ \xi^p \end{bmatrix}_{(np\times n)}$, $\Psi_y = \begin{bmatrix} \Psi\xi \\ \vdots \\ \Psi\xi^p \end{bmatrix}_{(np\times n)}$,

, $U(k) = \begin{bmatrix} u(k) \\ \vdots \\ u(k+m-1) \end{bmatrix}_{(m\times 1)}$, $\hat{Y}(k) = \begin{bmatrix} Y(k+1) \\ \vdots \\ Y(k+p) \end{bmatrix}_{(np\times 1)}$,

$$\varphi_x = \begin{bmatrix} \varphi & 0 & 0 \\ \vdots & \vdots & 0 \\ \xi^{m-1}\varphi & \cdots & \varphi \\ \vdots & & \vdots \\ \xi^{p-1}\varphi & \cdots & \sum_{i=0}^{p-m} \xi^i \varphi \end{bmatrix}_{(p\times m)}, \Theta_y = \begin{bmatrix} \Psi\varphi & 0 & 0 \\ \vdots & \ddots & 0 \\ \Psi\xi^{m-1}\varphi & \cdots & \Psi\varphi \\ \vdots & & \vdots \\ \Psi\xi^{p-1}\varphi & \cdots & \sum_{i=0}^{m-p+1} \Psi\xi^{i-1}\varphi \end{bmatrix}_{(p\times m)}$$

3.2 Rolling optimization:

To minimize the difference between the predicted inventory value "$\hat{Y}(k)$" and the desired target inventory value "$R(k)$", it is expressed using the cost function:

$$\begin{aligned} \min J(k) &= \min\left\|\hat{Y}(k) - R(k)\right\|_Q^2 + \|U(k)\|_R^2 \\ &= \left(\hat{Y}(k) - R(k)\right)^T Q \left(\hat{Y}(k) - R(k)\right) + U(k)^T R U(k) \end{aligned} \tag{4}$$

where "$Q = diag(q_1 \quad q_2 \quad \cdots \quad q_p)$" , "$R = diag(r_1 \quad r_2 \quad \cdots \quad r_m)$"
The optimal production/order quantity can be obtained by solving equation (4).

$$U(k) = -\left(\Theta_y^T Q \Theta_y + R\right)^{-1} \Theta_y^T Q(\Psi_y x(k) - R(k)) \tag{5}$$

In practical situations, there are constraints on production/ordering and inventory.

$$U_{\min}(k) \leq U(k) \leq U_{\max}(k) \tag{6}$$

$$\hat{Y}_{\min}(k) \leq \Psi_y x(k) + \Theta_y U(k) \leq \hat{Y}_{\max}(k) \tag{7}$$

The bullwhip effect is the ratio of order quantity variance to demand variance in the supply chain. This paper select matrices $\overline{\Psi}$, and Θ for quantifying the bullwhip effect problem.

$$bullwhip_3 = \sqrt{\frac{x^T(k)\Psi^T\Psi x(k)}{d^T(k)d(k)}} + \sqrt{\frac{u^T(k)\Theta^T\Theta u(k)}{d^T(k)d(k)}} \tag{8}$$

4 Simulation Analysis

Figure 2 illustrates the MPC structure diagram for the multi-source-multi-channel closed-loop supply chain in Simulink. Using the inventory of each node in reference [7], conduct a quantitative analysis of the inventory of each node in this article. Where, the nominal inventory levels for the supplier, branch livestreaming warehouse, self-media livestreaming warehouse, retailer, third-party recycler, and consumer are 300, 150, 250, 150, 3, and 30, respectively. The actual inventory levels are 100, 80, 80, 80, 0, and 60. respectively. The remaining parameters are： $\alpha_1 = 0.1, = 0.7, \alpha_3 = 0.1, \alpha_4 = 0.1, \beta_1 = 0.2, \beta_2 = 0.8, \beta_3 = 0.2, \beta_4 = 0.2, \mu = 0.1, \delta = 0.8, \lambda = 0.1$.

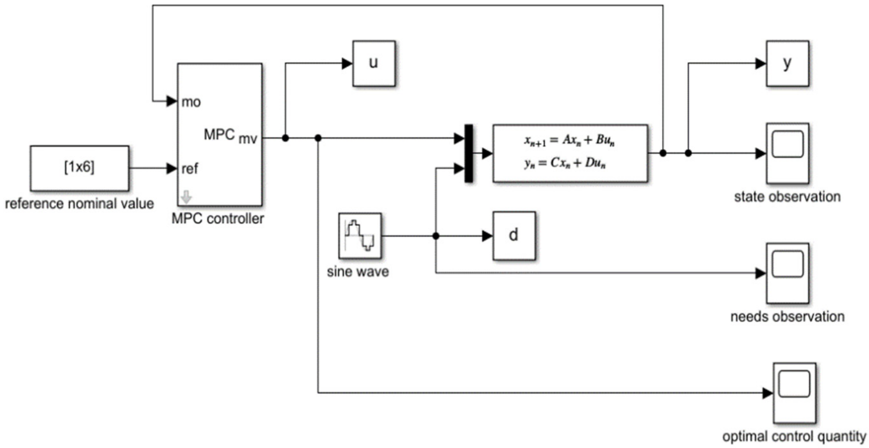

Fig. 2. MPC structure diagram

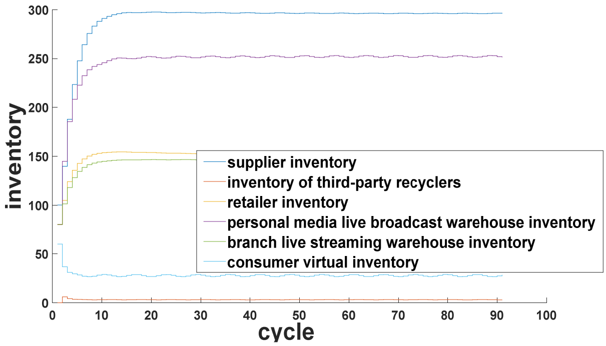

Fig. 3. The all system inventory diagram

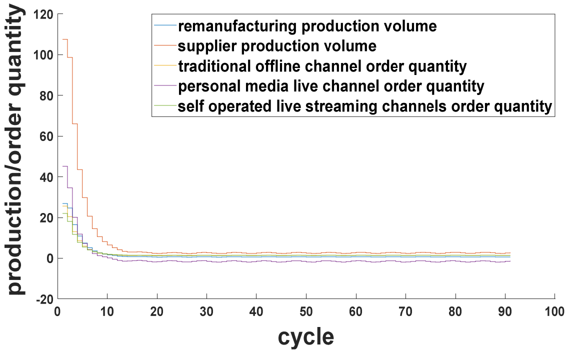

Fig. 4. The production/ordering diagram

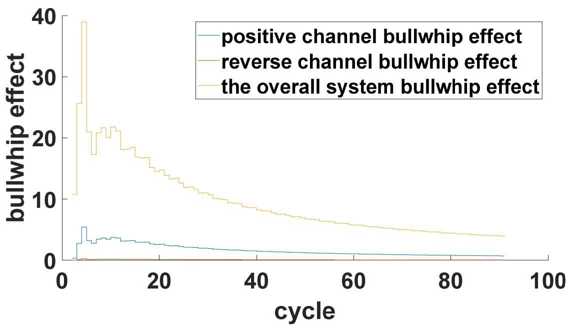

Fig. 5. Bullwhip Effect among Conclusion

Under MPC control, inventory at each node has reached the expected level, avoiding backlog. Figure 3 shows the inventory levels for the entire system. Order quantities gradually stabilize after 10 cycles, as shown in Figure 4. Figure 5 shows MPC's effective mitigation of the bullwhip effect in three supply chain channels.

5 Conclusion

Using MPC in a multi-source-multi-channel closed-loop supply chain, with a focus on the impact of live streaming. Simulation analysis was conducted using Simulink, which successfully optimized inventory, alleviated the bullwhip effect, and ensured the dynamic performance of the system.

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