

# EXTENDED STATE OBSERVER-BASED OPTIMIZED SYNERGETIC CONTROL FOR PRODUCTION-INVENTORY SYSTEMS

Aws M. Abdullah<sup>1</sup>, Zainab D. Hussein<sup>2</sup>, Nagham Y. Naji<sup>3</sup>, Lamia S. Mashkoor<sup>4</sup>, Hussien Dulaimi<sup>5\*</sup>, Huthaifa Al-Khazraji<sup>6</sup>, Luay T. Rasheed<sup>7</sup>

<sup>1, 2, 3, 4</sup>University of Baghdad, Baghdad, Iraq

<sup>5, 6, 7</sup>University of Technology-Iraq, Baghdad, Iraq

Email: <sup>1</sup>[aws.abd@cois.uobaghdad.edu.iq](mailto:aws.abd@cois.uobaghdad.edu.iq), <sup>2</sup>[Zainab.d@rashc.uobaghdad.edu.iq](mailto:Zainab.d@rashc.uobaghdad.edu.iq), <sup>3</sup>[nagham.y@cois.uobaghdad.edu.iq](mailto:nagham.y@cois.uobaghdad.edu.iq), <sup>4</sup>[lamia.s@cois.uobaghdad.edu.iq](mailto:lamia.s@cois.uobaghdad.edu.iq), <sup>5\*</sup>[hussien.s.mohammed@uotechnology.edu.iq](mailto:hussien.s.mohammed@uotechnology.edu.iq), <sup>6</sup>[huthaifa.k.ibrahim@uotechnology.edu.iq](mailto:huthaifa.k.ibrahim@uotechnology.edu.iq), <sup>7</sup>[luay.t.rasheed@uotechnology.edu.iq](mailto:luay.t.rasheed@uotechnology.edu.iq)

**Abstract** - The efficient exploitation of production inventory systems is of significant importance in the modern industrial reality. This paper explores the effect of such a system on dynamic behaviour of a system when the control is provided synergistically by a method called synergetic control (SC). The mathematical model of the system is first constructed and SC introduced to improve the responsiveness of the system when the time-varying demand condition is taken into account. To cope with the problem of unavailability of the systems' state signals and to estimate the demand, the extended state observer (ESO) is introduced. Moreover, mountain gazelle optimizer (MGO) is employed to tune the adjustable design parameters of the SC and the ESO based on the integral of absolute error (IAE). The enhanced ability of the extended state observer (ESO) to provide an estimate of the system states and profiles of the demand can be verified by numerical simulations utilizing in MATLAB software. Moreover, the performance of the proposed ESO-SC is compared with the proportional-integral-derivative (PID) controller. These results demonstrate that the ESO-SC achieves superior performance enhancement, particularly through a significant reduction in inventory costs.

**Keywords:** Production-inventory system, Synergetic control, Extended state observer, Mountain gazelle optimizer, Proportional-integral-derivative controller.

## 1. Introduction

The increasingly of the complexity of the business process has put a lot of pressure on the decision-maker to understand the dynamics of the supply chain. The supply chains have taken a global presence, even in the case of a seemingly simple product. The chain in the automotive manufacturing industry holds a large percentage of corporate value; therefore, the needs to shield the chain against small disruptions in the delivery time, and at the same time perform optimally, is paramount [1]. The supply chain is a coordinated process and involves the suppliers, production plants, warehouses, and manufacturers that work in liaison to acquire unprocessed raw materials, convert them into finished products, and distribute the finished products to the final consumer. In this context, production-inventory control systems are also planned to ensure that raw material inventories,

work-in-process, and finished goods are maintained at the highest capabilities of giving maximum service with the least cost [2]. This objective can be ensured by optimizing the movement of information and goods between manufacturing and retailers within the business process [3]. In addition, increased competition in the business environment has encouraged production-inventory managers to seek for areas to improve firm profitability [4]. One way to reduce costs and to increase profitability is to reduce inventory levels as much as possible [5]. Due to uncertainties in the demand and the manufacturing environment, it is usually difficult for manufacturing companies to control production-inventory systems and achieve sustained cost-effective strategies.

Production-inventory problems have been successfully studied by control engineering practices over decades as an alternative way to model and control the performance of the system [6]-[7]. It was

found that these models adequately represent the industrial behaviour and can be directly used by the managers to determine the required order rates in the face of the fluctuated market demand. Variety of studies and approaches of control theory that are applied to production-inventory problems could be found in [8]-[11]. For example, Towill [12] investigated the ability of the proportional controller to improve the performance of the production-inventory system. Later, Jonn et al. [13] and AL-Khazraji et al. [14] extended Towill's work by adding other feedback information to the system. Towill et al. [15] showed that the Proportional plus Integral (PI) controller could eliminate the inventory deficit in the production-inventory system. Tosetti et al. [16] and White and Censlive [17] implemented the Proportional-Integral-Derivative (PID) controller. Sarir and Abderhmane [18] proposed a PID controller which has increased fuzzy logic and the gains are mechanically fine-tuned through ant colony optimization (ACO), using the ISE. Al-Khazraji [19] studied the effect of an optimal integral-minus-proportional-derivative (I-PD) controller on the dynamic behaviour of the production-inventory system. Cuckoo Search Optimization (CSO) and an improved version of CSO (ICSO) were two swarm-based optimization strategies that have been used to optimize the adjustable parameters of the I-PD controller. Two simulation scenarios were implemented, one step change in unit step demand and the other stochastic demand. As shown in the results of the simulations, the IC-SOC approach performed better than the traditional CSO method in the process of tuning of the I-PD controller.

Synergetic control (SC) theory [20] offers a systematic and powerful framework for controller synthesis, enabling effective regulation and stabilization of a wide range of dynamical systems such as position tracking control of the magnetic levitation system [21], controlling the wind turbine system [22], improving the performance of overhead crane system [23], induction motor speed control [24]. Motivated by the aforementioned works, this paper presents a SC method for enhancing production-inventory responsiveness under bounded time-varying demand. SC is a model-based control method and the states of the system are required to generate the control law. In many control systems, not all the relevant system states directly can be measured. SC is therefore impossible without auxiliary ways of estimation. The challenge is solved by using observers [25]-[26], which make it possible to estimate a state fully using single output measurements. Besides, production-inventory system is vulnerable to time-varying demand; to cope with these difficulties, an extended state observer (ESO) has been presented which can estimate both the state vector and the demand trajectory. The use of meta-heuristic optimization algorithms in modern research is often based on the

need to establish parameters of the controllers and observers as they have better performance during the process of establishing the parameters, compared to the main ad hoc tuning processes [27]-[29]. In this regard, the Mountain Gazelle Optimizer (MGO) is invited to solve the parameter-selection problem in this research. Its nature-inspired metaheuristic algorithm and used to solve complex optimization problems with an effective balance of exploration and exploitation [30].

This paper has made the following key contributions:

1. The production inventory system is subjected to a time varying demand environment and a synergetic-control-based approach is used.
2. A long state observer is developed to give the exact estimation of the system states and the time depending demand.
3. The effectiveness of the suggested observer-controller couple is also improved with the help of using Mountain Gazelle Optimizer.
4. The performance of the proposed approach is compared with the performance of the PID controller.

## 2. Methodology

The basic aim of the production-inventory system controller implemented is to keep the inventory at a set level through controlling the order rate [31]. Therefore, the methodology to address the objective of this paper is as follows: the mathematical model of production-inventory system is derived. The next step is to design the action law of the synergetic control (SC) to achieve the desired inventory response. To estimate systems' state signals and the time-varying demand, in the third stage, the extended state observer (ESO) is developed. The mountain gazelle optimizer (MGO) is employed in the fourth stage to tune the adjustable design parameters of the SC and the ESO based on the Integral of Absolute Error (IAE).

### 2.1. Production-Inventory System

A production-inventory system is an essential unit in the supply chain that combines orders decision, production process and the inventory. It is assumed that the demand rate for the product  $d$  is bounded time-varying demand. The state variable  $x_1$  measures the level of the inventory. The state variable  $x_2$  refers to the production rate. If the production of the product is completed then it is dispatched to inventory and/or sale to customer to fulfilment the demand. These operational actions are best represented by using an exponential transfer function. On other words, the process of production is modelled as a first-order lag with a time constant of  $T_p$ . The time constant of the production process

refers to the time required between receiving an order and delivering the item as a finished product [32]. The order rate  $u$  is the control input to the system. Production-inventory systems can be expressed as either continuous-time or discrete-time system. As an example, it is possible to compare continuous-review production rate and inventory information with periodic review schemes [33]. Based on this, here the current model takes the form of continuous-time. The system governing equations are written in the form [19]:

$$\dot{x}_1 = x_2 - d \tag{1}$$

$$\dot{x}_2 = \frac{1}{T_p}(u - x_2) \tag{2}$$

### 2.2. Synergetic Control

SC is a feedback control technique that can be applied to various dynamical systems to improve the performance of the system. It can be best described as a control methodology that enforces desired system behaviour by forcing the system dynamics to move onto a predefined invariant manifold, called the synergetic manifold, and keeping them there through continuous control action [34]. Let's define  $e$  as the error between the actual and the desired inventory level as:

$$e = x_r - x_1 \tag{3}$$

Taking the derivative of the error gives:

$$\dot{e} = \dot{x}_r - \dot{x}_1 \tag{4}$$

By substituting Eq. (1) in Eq. (4) gets:

$$\dot{e} = \dot{x}_r - x_2 + d \tag{5}$$

Taking the second derivative of the error gives:

$$\ddot{e} = \ddot{x}_r - \dot{x}_2 + \dot{d} \tag{6}$$

Substitute Eq. (2) in Eq. (6) obtains:

$$\ddot{e} = \ddot{x}_r - \frac{1}{T_p}(u - x_2) + \dot{d} \tag{7}$$

Define a macro-variable  $\psi$  as:

$$\psi = c_1 e + \dot{e} \tag{8}$$

Taking the derivative of the macro-variable  $\psi$  gives:

$$\dot{\psi} = c_1 \dot{e} + \ddot{e} \tag{9}$$

Substitute Eq. (6) in Eq. (8) obtains:

$$\dot{\psi} = c_1 \dot{e} + \ddot{x}_r - \frac{1}{T_p}(u - x_2) + \dot{d} \tag{10}$$

The desired dynamic evolution of the macro-variable is chosen as [35]:

$$\dot{\psi} + c_2 \psi = 0 \tag{11}$$

Substituting Eq. (10) in Eq. (11) gives:

$$c_1 \dot{e} + \ddot{x}_r - \frac{1}{T_p}(u - x_2) + \dot{d} + c_2 \psi = 0 \tag{12}$$

Select  $u$  as follows:

$$u = T_p \left( c_1 \dot{e} + \ddot{x}_r + \frac{x_2}{T_p} + \dot{d} + c_2 \psi \right) \tag{13}$$

where  $c_1$  and  $c_2$  are positive constant represents the design coefficients for the SC.

### 2.3. Extended State Observer

In this sub section, an elaborate design of an extended state observer (ESO) of the production-inventory control system is given. The core of the design principle implies the extension of system model in such a way that disturbances and the uncertainties are considered to be part of an extended state [36]. The mathematical model obtained above Eqs, mutually adjusted to yield the desired outcome, must be implemented in order to implement the ESO. The utilization of (1) and (2) is supplemented by the third state  $x_3 = d$ , as follows:

$$\dot{x}_1 = x_2 + x_3 \tag{14}$$

$$\dot{x}_2 = \frac{1}{T_p}(u - x_2) \tag{15}$$

$$\dot{x}_3 = \dot{d} \tag{16}$$

The ESO can be therefore synthesized as given in [37]:

$$\dot{z}_1 = z_2 - z_3 + h_1(x_1 - z_1) \tag{17}$$

$$\dot{z}_2 = \frac{1}{T_p}(u - z_2) + h_2(x_1 - z_1) \tag{18}$$

$$\dot{z}_3 = h_3(x_1 - z_1) \tag{19}$$

In this case, the observer declares that the true system states,  $x_1$  and  $x_2$ , will be estimated by the observer state,  $z_1$  and  $z_2$ , respectively; the observer state,  $z_3$  will estimate the time-varying demand. The design coefficients of the ESO are represented by positive constants  $h_1, h_2$ , and  $h_3$ .

### 2.4. Mountain Gazelle Optimizer

The Mountain Gazelle Optimization (MGO) algorithm is based on the behavioural ecology of the mountain gazelles in their usual environment. These are Arabian Peninsula-endemic ungulates, which are highly territorial as the ecological niche on Robinin species, which causes a geometric separation between individuals. They are furthered into three different social strata, namely parental-offspring-territories, juvenile-male-territories, and single-male-territories [38]. MGO optimization framework integrates the five main mechanisms namely, the non-grouping dynamics, staghorn male aggregations, maternity group interactions, zone marking of males, and migratory cycles necessitating foraging needs [39].

### 2.4.1. Migration Process

The subject of territorial and reproductive competition in mountain gazelles is outlined. Every person is in a separate and secluded place. The male juveniles strive towards marking out female-bearing territories and they simultaneously protect their territories. This interaction can be mathematically formalized as in Eq.s (20) - (24) [40]:

$$M_e = m_g - |(ri_1 \times ZM - ri_2 \times L(t) \times R)| \times rv \quad (20)$$

$$ZM = L_{ra} \times [r_1] + M_{pr} \times [r_2], ra = \left\{ \left\lfloor \frac{N}{3} \right\rfloor \dots N \right\} \quad (21)$$

$$R = N_1(D) \times e^{-it \times \left(\frac{2}{maxit}\right)} \quad (22)$$

$$rv = \begin{cases} (\alpha + 1) + r_3 \\ \alpha \times N_2(D) \\ r_4(D) \\ N_3(D) \times N_4(D)^2 \times \cos((r_2 \times 2) \times N_3(D)) \end{cases} \quad (23)$$

$$\alpha = -1 + it \times \left(\frac{-1}{maxit}\right) \quad (24)$$

In which, the terms  $m_g$  and  $ri_1$  and  $ri_2$  indicate random variables in sampling, and  $rv$  represents a coefficient vector declared at each step,  $L_{ra}$  represents a random variable in the species  $ra$ , and  $M_{pr}$  indicates the average of the population of agents. This is a number of agents,  $N$ .  $r_3$  and  $r_4$  are uniformly distributed random numbers between 0 and 1, and  $N_1(D)$  value of the base distribution is picked randomly by a random distribution between two values, it and  $maxit$ .  $N_2$ ,  $N_3$ , and  $N_4$  are random numbers in the natural space or discrete space and denote issue sizes.

### 2.4.2. Maternity Groups

In this section, gives emphasis on the presence of maternity groups in the life cycle of mountain gazelles with the need to eliminate competition among prevailing stags. These are the mathematical representations presented in Eq. (25):

$$MG = (ZM + rv) + (ri_3 \times m_g - ri_4 \times r_{rand}) \times rv \quad (25)$$

In the equation (25), the representation of the position of an agent that is randomly selected among the whole population is denoted as  $r_{rand}$ ,  $ri_3$  and  $ri_4$  are non integer random variables, and continuous random variables, respectively.

### 2.4.3. Stag Male Groups

This section looks at the power politics between young men and adult men where the latter desire to establish territorial and procreation rights over the female. These practices are fixed in Eq.s (26)-(27) [41]:

$$STG = (L(t) - D) + (ri_5 \times m_g - ri_6 \times MG) \times rv \quad (26)$$

$$D = (|L(t)| + |m_g|) + (2 \times r_6 - 1) \quad (27)$$

In equations, (26) - (27), the variables  $ri_5$  and  $ri_6$  are selected at random, as integers randomly chosen 1 or 2 and that is all. The agent positions at the time of iteration  $t$  and the corresponding random value are denoted by  $L(t)$  and  $r_6$ , respectively.

### 2.4.4 Migration Process

This section describes the locomotor mastery of the gazelles whereby it was observed that they cover long distances in their quest to forage. The mathematical formulation of the same is described in the Eq. (28):

$$M = (UB - LB) \times r_7 + LB \quad (28)$$

where  $UB$  and  $LB$  are the upper and lower limits.

## 3. Computer Simulation Results

In this section, the effectiveness of the proposed extended state observer (ESO) in estimating the actual states and the time-varying demand of the system and designing the SC for controlling the inventory level is evaluated. For this purpose, the computer-simulation based on MATLAB-program has been conducted. MATLAB is an efficient tool that can be used to design and simulate different control algorithms. The equations of the production-inventory system that are given in Eq. (1) and Eq. (2) have been coded to capture the dynamic of the system. The time constant of  $T_p$  of the system is one day. The duration simulation time is 120 days. In order to test the proposed control scheme on the realistic demand scenarios, demand is simulated based on a stationary, identically and independently distributed random process. The model of production-inventory that is used is linear, which means that the unmet demand can be back-order; thus, negative values of the inventory levels are synonymous with back-order quantity. Besides, there is no limitation in the production capacity. Lastly, a negative order rate is not allowed.

One of the most important issues in a successful design of an algorithm of production-inventory control is to choose a proper evaluation measure that controls system efficiency, customer value delivery, and allocation to project organizational objectives. In the context of the control theory, many of time domain performance measures are used. In this paper the integral of absolute error (IAE) is used as a quantitative error measure to determine the effectiveness of the proposed control algorithm. Therefore, the adjusted design parameters of the ESO-SC that is applied to regulate the inventory level

is computed by MGO using IAE as an objective function as given in Eq. (29).

$$IAE = \int_0^{t_s} |e| dt \quad (30)$$

We use  $t_s$  to refer to the simulating time, and  $e$  to refer to the error between the real inventory and the target inventory. The Integrated Absolute Error (IAE) measure corrects both positive errors and negative errors incurred in an evenhanded manner that suggests that the cost incurred by having an excess inventory (holding cost) and the cost incurred by having less inventory (backorder cost) is penalized equally. The minimum IAE means the system has a better inventory level responsiveness, in other words, has less inventory cost. To achieve the target level of inventory, which is endorsed as zero in the current research, it is necessary to aim at enforcing the Just-in-Time (JIT) strategy.

The first case is the simulation of an open-loop test in order to estimate the system conditions and temporal demand profile. The initial value of the states of the system ( $x_1$  and  $x_2$ ) was set to (0 and 0) respectively. Based on the MGO, the parameters of ESO were obtained as follows:  $h_1 = 60$ ,  $h_2 = 280$  and  $h_3 = 440$ . It can be seen from Fig. 1 and Fig. 2 that the ESO is successfully estimating all states of the system and the demand. Fig. 3 and Fig. 4 show the estimation error of  $x_1$ ,  $x_2$  and  $d$ .

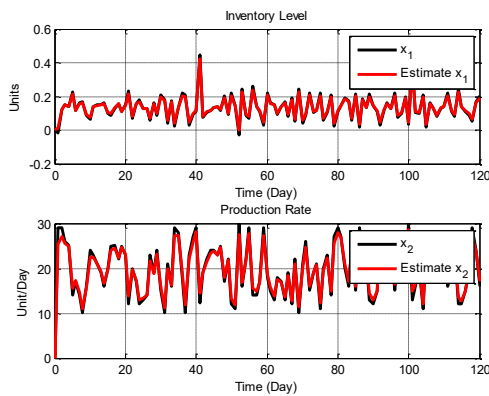


Figure 1: The performance of ESO to estimate  $x_1$  and  $x_2$

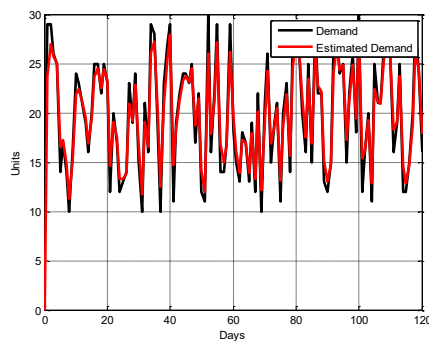


Figure 2: The performance of ESO to estimate demand

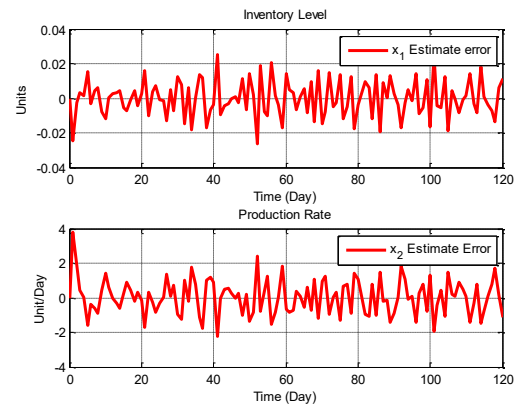


Figure 3: Estimate error of  $x_1$  and  $x_2$

In the next case, a controlled mechanism based on the ESO-SC is applied to manage inventory during time-dependent demand. The outcomes of the ESO-SC will be compared with classical PID control. Based on the MGO, the tuneable parameter of the SC is obtained as follows:  $c_1 = 15$  and  $c_2 = 50$ , and for the PID is obtained as follows:  $K_p = 75$ ,  $K_i = 10$  and  $K_d = 2$ . The simulation result for the inventory level and the production rates of the two controlled systems is shown in Fig. 5. Fig. 5 indicates that the proposed ESO-SC has better regulating performance to keep the inventory level close to zero than the PID controller.

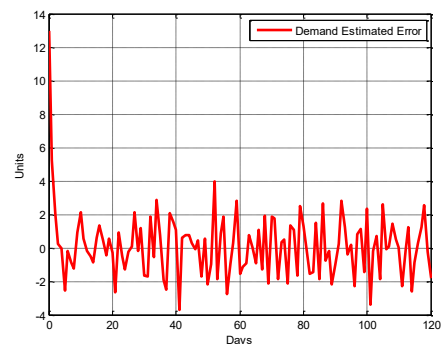


Figure 4: Estimate error of demand

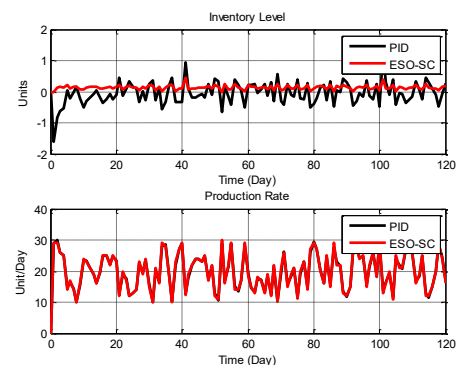


Figure 5: Production-inventory response based on ESO-SC and PID

To ensure the effectiveness of the proposed control algorithm, another simulation is conducted for different a stationary, identically and independently distributed random demand. On this simulation, the same tuneable parameter of the ESO-SC and for the PID controller is used. Fig. 6 and Fig. 7 show the estimating of the states of the system and the demand. Fig. 8 and Fig. 9 show the estimation error of  $x_1$ ,  $x_2$  and  $d$ . The simulation result for the inventory level and the production rates of the two controlled systems is shown in Fig. 10.

The two scenarios of the computer simulations reveal that the ESO can accurately estimate the states and the unknown demand. Moreover, the ESO-SC can achieve good regulation for the inventory control.

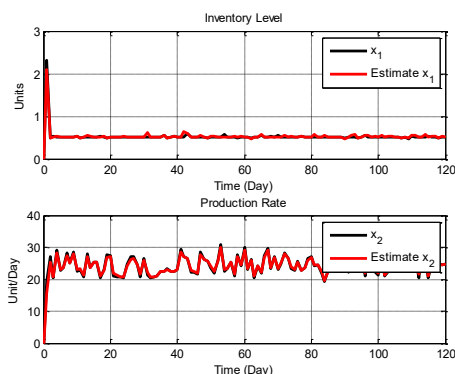


Figure 6: The performance of ESO to estimate  $x_1$  and  $x_2$

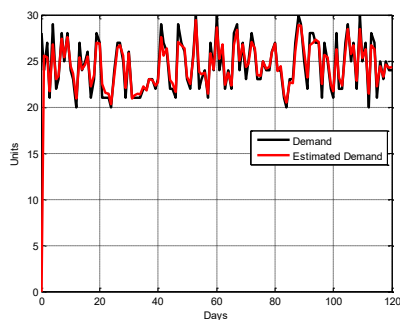


Figure 7: The performance of ESO to estimate demand

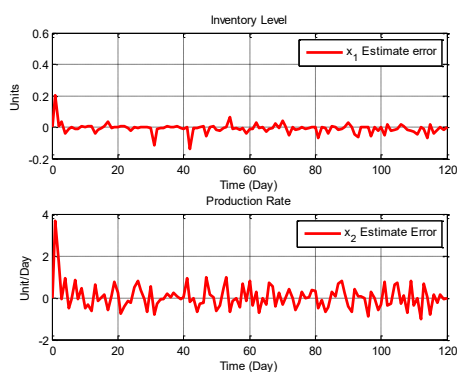


Figure 8: Estimate error of  $x_1$  and  $x_2$

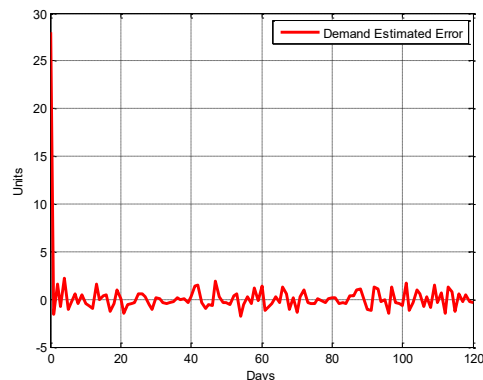


Figure 9: Estimate error of demand

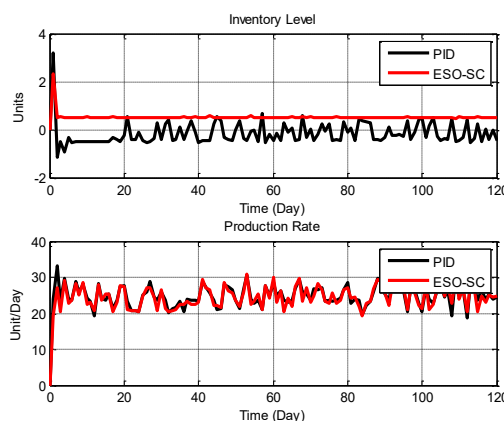


Figure 10: Production-inventory response based on ESO-SC and PID

#### 4. Conclusion

One of the critical units of the optimized supply chain networks is production-inventory systems. This paper presents a robust and effective inventory management system. The primary challenges are the uncertainty associated with time-dependent demand, which necessitates a robust and consistent control policy. In this regard, a new methodology consisting of combining an extended state observer and synergetic control is suggested to maintain the level of inventory at the desired level. The Mountain Gazelle Optimizer is used in the tuning of the observer-controller design parameters. The obtained control scheme is simulated and evaluated using MATLAB, the findings of which show that the controller provides correct control of inventory levels in the presence of demand uncertainty. The effectiveness of the suggested strategy is also supported by the comparison of simulations with a PID controller. However, more research is also necessary to cover gaps in production lead times as well as the handling of perishable products. Moreover, this work also could be extended to incorporate production capacity in the model.

## References

- [1] A.S. White and M. Censlive, "An alternative state-space representation for APVIOBPCS inventory systems," *Journal of Manufacturing Technology Management*, vol. 24, no. 4, pp.588-614, 2013.
- [2] A.S. Jaboob, A.M.B. Awain, K.A.M. Ali, and A.M. Mohammed, "Introduction to operation and supply chain management for entrepreneurship," In *Applying Business Intelligence and Innovation to Entrepreneurship*, 2024, pp. 52-80.
- [3] J.D. Schwartz and D.E. Rivera, "A process control approach to tactical inventory management in production-inventory systems." *International Journal of Production Economics*, vol. 125, no. 1, pp.111-124, 2010.
- [4] B. Ponte, J. Costas, J. Puche, R. Pino and D. de la Fuente, "The value of lead time reduction and stabilization: A comparison between traditional and collaborative supply chains." *Transportation Research Part E: Logistics and Transportation Review*, vol. 111, pp.165-185, 2018.
- [5] S. Tosetti, D. Patino, F. Capraro and A. Gambier, "A new inventory level APIOBPCS-based controller." In *2008 American Control Conference [IEEE]*, 2008a, pp. 2886-2891.
- [6] E. Aggelogiannaki, P. Doganis and H. Sarimveis, "An adaptive model predictive control configuration for production-inventory systems." *International Journal of Production Economics*, vol. 114, no. 1, pp.165-178, 2008.
- [7] H. AL-Khazraji, C. Cole and W. Guo, "Analysing the impact of different classical controller strategies on the dynamics performance of production-inventory systems using state space approach." *Journal of Modelling in Management*, vol. 13, pp. 211-235, 2018.
- [8] M. Ortega and L. Lin, "Control theory applications to the production-inventory problem: a review." *International Journal of Production Research*, vol. 42, no. 11, pp.2303-2322, 2004.
- [9] H. Sarimveis, P. Patrinos, C.D. Tarantilis and C.T. Kiranoudis, "Dynamic modeling and control of supply chain systems: A review." *Computers & operations research*, vol. 35, no. 11, pp.3530-3561, 2008.
- [10] J. Orzechowska, A. Bartoszewicz, K.J. Burnham and D. Petrovic, "Control theory applications in logistics-MPC and other approaches." *Logistyka*, vol. 12, no. 3, pp.1769-1774, 2012.
- [11] A. Zemzam, M.E. Maataoui, M. Hlyal, J.E. Alami and N.E. Alami, "Inventory management of supply chain with robust control theory: literature review." *International Journal of Logistics Systems and Management*, vol. 27, no. 4, pp.438-465, 2017.
- [12] D.R. Towill, "Dynamic analysis of an inventory and order based production control system." *The international journal of production research*, vol. 20, no. 6, pp.671-687, 1982.
- [13] S. John, M.M. Naim and D.R. Towill, "Dynamic analysis of a WIP compensated decision support system." *International Journal of Manufacturing System Design*, vol. 1, no. 4, pp.283-297, 1994.
- [14] H. AL-Khazraji, C. Cole and W. Guo, "Dynamics analysis of a production-inventory control system with two pipelines feedback." *Kybernetes*, vol. 46, no. 10, pp.1632-1653, 2017.
- [15] D.R. Towill, G.N. Evans and P. Cheema, "Analysis and design of an adaptive minimum reasonable inventory control system." *Production Planning & Control*, vol. 8, no. 6, pp.545-557, 1997.
- [16] S. Tosetti, D. Patino, F. Capraro and A. Gambier. "Control of a production-inventory system using a PID controller and demand prediction." *IFAC Proceedings*, vol. 41, no. 2, 2008b, pp.1869-1874.
- [17] A.S. White and M. Censlive, "Using control theory to optimise profit in APVIOBPCS inventory systems." *Journal of Manufacturing Systems*, vol. 32, no. 4, pp.680-688, 2013.
- [18] H. Sarir, and B. Abderhmane, "Smart inventory control by using PID ACO controller and fuzzy logic controller," In *2022 14th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA)*, 2022, pp. 1-7.
- [19] H. Al-Khazraji, W. Guo, and A.J. Humaidi, "Improved cuckoo search optimization for production inventory control systems," *Serbian Journal of Electrical Engineering*, vol. 21, no. 2, pp.187-200, 2024.
- [20] A.N. Popov, "Synergetic synthesis of tracking control systems," In *IOP Conference Series: Materials Science and Engineering*, vol. 1029, no. 1, p. 012032, 2021.
- [21] F.R. Al-Ani, O.F. Lutfy, and H. Al-Khazraji, "Optimal Synergetic and Feedback Linearization Controllers Design for Magnetic Levitation Systems: A Comparative Study," *Journal of Robotics and Control (JRC)*, vol. 6, no. 1, pp.22-30, 2025.
- [22] R. Ettouil, K. Chabir, and M.N. Abdelkrim, "Optimal synergetic control for wind turbine system," *The International Journal of*

- Engineering and Science, vol. 7, no. 5, pp.44-48, 2018.
- [23] B. Hussain, A.I. Abdulkareem, and H. Al-Khazraji, "Optimal Synergetic and Feedback Linearization Controllers Design for Overhead Crane Systems: A Comparative Study," *International Journal of Robotics and Control Systems*, vol. 5, no. 4, pp.2178-2196, 2025.
- [24] Y.D. Son, T.W. Heo, E. Santi, and A. Monti, "Synergetic control approach for induction motor speed control," In 30th Annual Conference of IEEE Industrial Electronics Society, 2004. IECON 2004, vol. 1, pp. 883-887, 2004.
- [25] N.S. Mahmood, A.J. Humaidi, R.S. Al-Azzawi, and A. Al-Jodah, "Extended state observer design for uncertainty estimation in electronic throttle valve system," *International Review of Applied Sciences and Engineering*, vol. 15, no. 1, pp.107-115, 2024.
- [26] R.A. Mahmood, R.A. Kadhima, M. Nawfal, and H. Al-Khazraji, "High Gain Observer Based Backstepping Control Design for Nonlinear Single-Axis Driven Systems," *International Journal of Robotics and Control Systems*, vol. 5, no. 3, pp.1886-1899, 2025.
- [27] G. Yang, F. Lu, L. Wu, and J. Xu, "Design of particle swarm optimization adaptive sliding mode controller based on an extended state observer for the longitudinal motion of a supercavitating vehicle with input saturation," *Journal of Sensors*, vol. 2023, no. 1, p.2938089, 2023.
- [28] L.T. Rasheed, and M.K. Hamzah, "Design of an optimal backstepping controller for nonlinear system under disturbance," *Engineering and Technology Journal*, vol. 39, no. 3, pp.465-476, 2021.
- [29] F. R. Yaseen, M. Q. Kadhim, H. Al-Khazraji, A. J. Humaidi, "Decentralized Control Design for Heating System in Multi-Zone Buildings Based on Whale Optimization Algorithm," *Journal Européen des Systèmes Automatisés*, vol. 57, no. 4, pp. 981 - 989, 2024.
- [30] F. Anka, F.S. Gharehchopogh, G.G. Tejani, and S.J. Mousavirad, "Advances in mountain gazelle optimizer: a comprehensive study on its classification and applications," *International Journal of Computational Intelligence Systems*, vol. 18, no. 1, p.247, 2025.
- [31] D.N. Nya, and H. Abouaïssa, "An efficient framework for tactical management in supply chain systems," In 2022 14th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA), 2022, pp. 1-6.
- [32] A.S. White, and M. Censlive, "Analysis of the robustness of a single-tier pipeline inventory model," *International Journal of Inventory Research*, vol. 5, no. 4, pp.339-362, 2020.
- [33] S.M. Disney, D.R. Towill, and R. Warburton, "On the equivalence of the control theoretic, differential and difference equation approaches to solving the production and inventory control system design problem", 17 International conference on Production Research, 2003, pp.1-11.
- [34] A.A. Kolesnikov, "Introduction of synergetic control," In 2014 American control conference, 2014, pp. 3013-3016.
- [35] I. Kondratiev, R. Dougal, G. Veselov, and A. Kolesnikov, "Hierarchical control for electromechanical systems based on synergetic control theory," In 2009 IEEE Control Applications,(CCA) & Intelligent Control,(ISIC), 2009, pp. 495-500.
- [36] X. Yang, and Y. Huang, "Capabilities of extended state observer for estimating uncertainties," In 2009 American control conference, 2009, pp. 3700-3705.
- [37] B.Z. Guo and Z.I. Zhao, "On the convergence of an extended state observer for nonlinear systems with uncertainty," *Systems & Control Letters*, vol. 60, no. 6, pp.420-430, 2011.
- [38] B. Abdollahzadeh, F. S. Gharehchopogh, N. Khodadadi, and S. Mirjalili, "Mountain gazelle optimizer: A new nature-inspired metaheuristic algorithm for global optimization problems," *Advances in Engineering Software*, vol. 174, p. 103282, 2022.
- [39] M. Abdelsattar, A. Mesalam, A. Fawzi, and I. Hamdan, "Mountain gazelle optimizer for standalone hybrid power system design incorporating a type of incentive-based strategies," *Neural Computing and Applications*, vol. 36, no. 12, pp.6839-6853, 2024.
- [40] R. Abbassi, S. Saidi, S. Urooj, B.N. Alhasnawi, M.A. Alawad, and M. Premkumar, "An accurate metaheuristic mountain gazelle optimizer for parameter estimation of single-and double-diode photovoltaic cell models," *Mathematics*, vol. 11, no. 22, p.4565, 2023.
- [41] M.A. Karabiyik, B. Turkoglu, and T. Asuroglu, "Optimizing artificial neural networks using mountain gazelle optimizer", *IEEE Access*, vol. 13, pp. 50464-50479, 2025.