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Inventory Control for a Manufacturing System under Uncertainty: Adaptive Approach

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Abstract: This paper deals with controlling the in-process inventories for the manufacturing system of a typical machine-building enterprise which includes the machining, the transport, the storage bunker and the assembly line. The decision-making is implemented under uncertainty associated with the absence of exact machining model assuming that machine failures are also possible. To cope with this uncertainty, the adaptive control approach is proposed. Within this approach, a new adaptive reorder policy which makes it possible to improve the performance of the inventory control system is developed. Simulation experiments are conducted to demonstrate the advantage of this policy.

Keywords: Adaptation, estimation algorithms, identifiers, inventory control, production planning and scheduling, uncertainty.

1. INTRODUCTION

The in-process inventory control problem stated several decades ago, in particular, in Buchan and Koenigsberg (1963) remains a topic of considerable and widespread interest up to now. This problem is important from both theoretical and practical point of view. Since the pioneering works (Simon, 1952; Yokoyama, 1955), the classical control theory becomes a tool for dealing with the control of manufacturing systems containing the in-process inventories. A significant breakthrough in this research area has been made in Axsater (1985), Kuntsevich (1973), Shin *et al*. (2008), Skurikhin (1972), Wiendahl and Breithaupt (2000) who studied the dynamic processes arising in typical production control systems. Their ideas were extended in Azarskov *et al*. (2006), Zhiteckii *et al*. (2007).

Recently, different approaches inspired by novel results achieved in the modern control theory have been advanced to tackle the manufacturing control problems. Among them they include linear programming and dynamic programming, robust and adaptive control concepts, genetic algorithms, ℓ_1-optimization, etc. (Aharon *et al*., 2009; Azarskov *et al*., 2013; Bauso *et al*., 2006; Boukas, 2006; Grubbstrom and Wikner, 1996; Hennet, 2003; Hoberg *et al*., 2007; Ignaciuk and Bartoszewic, 2010; Kostić, 2009; Rodrigues and Boukas, 2006; Taleizadeh *et al*., 2009; Towill *et al*., 1997).

To implement a perfect inventory control for a manufacturing system, the exact mathematical model with respect to the machining is required (Skurikhin, 1972). In practice, however, there is only approximate model of the machining that may be used in the decision-making system. Moreover, machine failures are possible, in principle. Due to these facts, there is some uncertainty when the order (reorder) policy is formed (Azarskov *et al*., 2006; Zhiteckii *et al*., 2007). The two approaches are proposed in modern control theory to deal with uncertainty: either a nonadaptive robust approach (Sanchez-Pena and Szanier, 1998) or an adaptive approach (Landau *et al*., 1997).

In this paper, the adaptive control concept is extended to cope with uncertainty in the inventory control. Its main contribution is a new adaptive control algorithm that makes it possible to improve the decision-making system via the use of a novel reorder policy formed by this system. Contrary to (Azarskov *et. al*., 2013), it does not require *a priori* information related to some bounds on uncertainty. This feature seems to be important from a practical point of view.

2. DESCRIPTION OF A BASIC INVENTORY CONTROL SYSTEM

2.1 Mathematical Model

Consider the system for controlling the so-called in-process inventory (Buchan and Koenigsberg, 1963, Chap. 22) of a typical machine-building enterprise whose production line includes the machining, the transport, the storage and the assembly line depicted diagrammatically in Fig. 1. This control system operates as follows. At the start $t = t_n := nT_0$ of each nth scheduled time interval $[t_n, t_{n+1}]$ $(n = 0, 1, 2, \ldots)$ having the same duration $T_0 = t_{n+1} - t_n$, the decision-making system sends the request about the current product stock level $H(t)$ equal to $H(t_n) := H_n$. After receiving this information, the deviation

$$e_n := r^0 - H_n \qquad \text{(in units)} \tag{1}$$

of H_n from the required level of safety stock value, r^0, is determined. Next, it places the order (reorder), θ_n, defining the product volume to be produce during the planning interval $t_n \le t \le t_{n+1}$ in accordance with the rule

$$\theta_n = \begin{cases} \theta_{\max} & \text{if} \quad \theta_n^{c} > \theta_{\max}, \\ \theta_n^{c} & \text{if} \quad 0 \le \theta_n^{c} \le \theta_{\max}, \\ 0 & \text{if} \quad \theta_n^{c} < 0, \end{cases} \qquad \text{(in units)} \tag{2}$$

where $\theta_{\max}$ denotes maximum order size which might be satisfied at $t \in [t_n, t_{n+1}]$ by introducing all available manufacturing capacity, and θ_n^{c} is defined by a given order policy. Usually (Kuntsevich, 1973; Skurikhin, 1972) θ_n^{c} is specified by

$$\theta_n^{c} = e_n \qquad \text{(in units).} \tag{3}$$

The expression (2) together with (1) and (3) implies that if $H_n > r^0$ then $\theta_n = 0$ because the order quantity θ_n cannot be negative. Note that (3) corresponds to the simplest order policy.

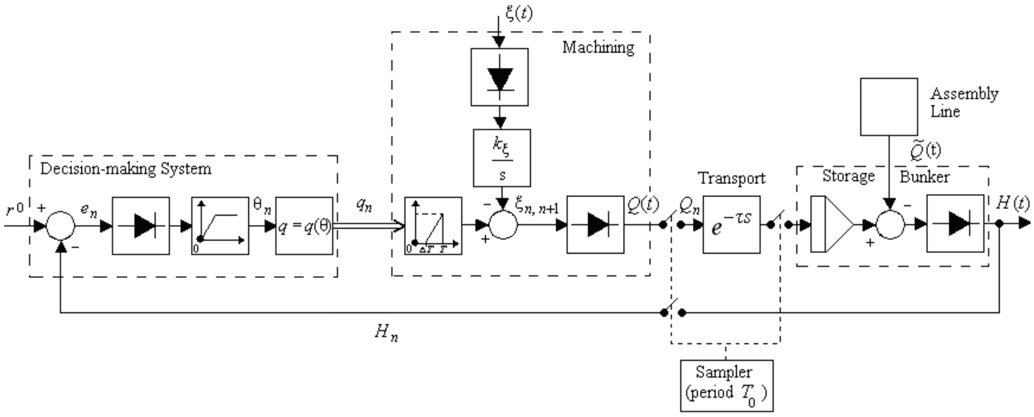

Fig. 1. Configuration of the basic inventory control system.

Based on the value of θ_n, the decision-making system determines the production capacity q_n necessary to produce the order quantity θ_n. This capacity may be expressed as

$$q_n = q(\theta_n) \tag{4}$$

with some vector-valued operator q. Equation (4) gives formally an operation schedule for each machine.

The product fabricated by machining to the end of time interval $[t_n, t_{n+1}]$ is

$$Q_{n+1} = P_{n,\,n+1}(q_n) - \xi_{n,\,n+1} \qquad \text{(in units)} \tag{5}$$

where $P_{n,\,n+1}$ represents, in general, the time-varying operator. $\xi_{n,\,n+1}$ may be understood as an additive non-negative noise $(\xi_{n,\,n+1} \ge 0)$ caused by the machine failure during a time range $\Delta T \le \Delta T_{\max} < T_0$. It is assumed that $\xi_{n,\,n+1}$ is an irregular bounded variable.

As in Azarskov *et al*. (2006), Skurikhin (1972) and Zhiteckii *et al*. (2007), it is assumed that all the product whose quantity Q_{n+1} is delivered through the intermediate transport to the storage at the time instant $t = t_{n+1} + \tau$ with some time delay $\tau < T_0$. The product is taken from the storage bunker on the demands coming from the assembly line with a rate $k(t) \ge 0$. Thus, for all time the stock level $H(t)$ varies so that it decreases "continuously" until the lot of size Q_{n+1} arrives to the storage when $H(t)$ increases step-wise. Fig. 2 illustrates such a typical inventory history over the time interval $[t_{n+1}, t_{n+2}]$.

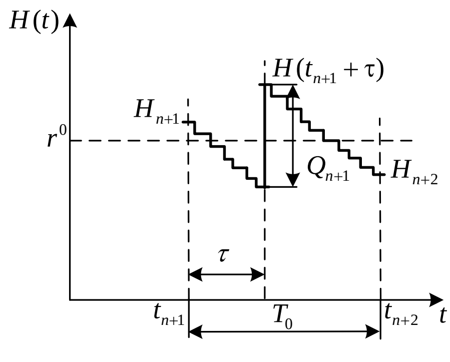

Fig. 2. Inventory level.

The lot size $\nabla\tilde{Q}_{n+1,\,n+2}$ taken on the demand of the assembly line from storage bunker during the period $t_{n+1} \le t \le t_{n+2}$ is

$$\nabla\tilde{Q}_{n+1,\,n+2} = \int_{t_{n+1}}^{t_{n+2}} k(t)\, dt \qquad \text{(in units)} \tag{6}$$

where $k(t)=0$ if only $H(t)=0$ because $H(t)$ cannot be negative. Then the inventory level H_{n+2} at the time instant $t=(n+2)T_0$ will be given as

$$H_{n+2} = H_{n-1} - \nabla\tilde{Q}_{n+1,\, n+2} + Q_{n+1} \quad (7)$$

with $\nabla\tilde{Q}_{n+1,\,n+2}$ determined by (6).

Equations (1)–(7) define the mathematical model of the in-process inventory control system.

2.2 Features of Control System

The block diagram of the inventory control system described above is shown in Fig. 3. It is the feedback sampled-data system that includes the decision-making system (DMS), which is the controller with the parts 1 and 2 forming $\{\theta_n\}$ and $\{q_n\}$, respectively, and also the plant consisting of the machining (M), the transport (T) and the storage bunker (SB). The storage bunker as a part of this plant is subjected to the external disturbance $\tilde{Q}(t)$ going from the assembly lime (AL). Obviously, $\tilde{Q}(t)$ may be represented as follows:

$$\tilde{Q}(t) := \int_0^t k(t)\, dt$$

$$= \sum_{i=1}^{n} \nabla\tilde{Q}_{i+1,\, i+2} + \int_{t_n}^{t} k(t)\, dt, \qquad nT_0 \le t \le (n+1)T_0.$$

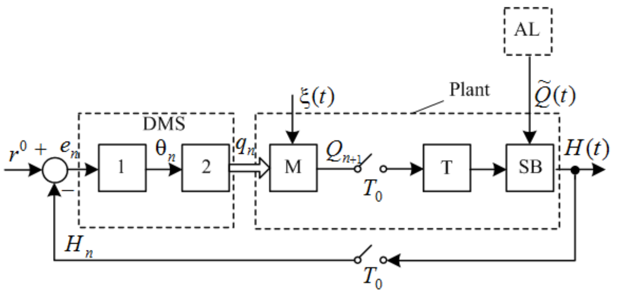

Fig. 3. Block diagram of inventory control system.

The essential assumption introduced here is that the lot sizes $\nabla\tilde{Q}_{n+i,\,n+i+1}$ which will be taken from storage bunker during the two time intervals $t_{n+1} \le t \le t_{n+2}$ and $t_{n+2} \le t \le t_{n+3}$ can exactly be predicted at each n as some variables $\nabla\tilde{Q}[n+i,\, n+i+1]$ $(i=0,1)$ using a technique considered in (Azarskov *et al.*, 2006).

Note that the storage bunker operates as an accumulator (the discrete integrator) whose output $H(t)$ is equal to

$$H(t) := H_0 + \sum_{i=1}^{n-1} Q_i - \int_{t_n}^{t} k(t)\, dt \qquad t \in [nT_0,\, nT_0 + \tau),$$

where H_0 denotes the initial inventory level.

From (5) together with (4) it follows that

$$Q_{n+1} = P_{n,\,n+1}(q_n(\theta_n)) - \xi_{n,\,n+1} \quad (8)$$

leading, in actual case, to $Q_{n+1} \ne \theta_n$ even when $\xi_{n,\,n+1} = 0$ because of the absence of the exact machining model. Defining the time-varying $\gamma_n = P_{n,\,n+1}(q_n(\theta_n))/\theta_n \le 1$ rewrite (8) as

$$Q_{n+1} = \gamma_n \theta_n - \xi_{n,\,n+1}. \quad (9)$$

In the ideal case when there is no machine failure ($\xi_{n,\,n+1} \equiv 0$), and the production model is known exactly implying $\gamma_n \equiv 1$, one has $\theta_{n+1} \equiv \theta_n$. For the better understanding of these cases, they are demonstrated in Fig. 4.

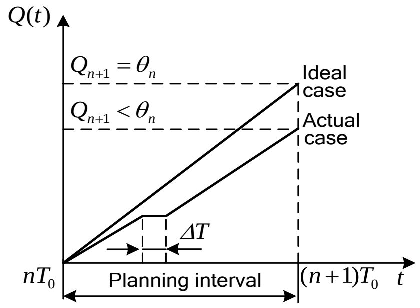

Fig. 4. Production processes.

Suppose that γ_n is a random coefficient which has possibly nonstochastic nature (Zhiteckii, 1996) and changes within the interval

$$\underline{\gamma} \le \gamma_n \le 1 \quad (10)$$

having a lower bound $\underline{\gamma}$, which remains unknown. Further, let

$$0 \le \xi_{n,\,n+1} \le \bar{\xi}, \quad (11)$$

where $\bar{\xi}$ representing the upper bound on $\xi_{n,\,n+1}$ is assumed to be known. Then (9) together with (10) and (11) yields

$$Q_{n+1} = \gamma\theta_n - \bar{\xi}/2 + v_{n,\,n+1}, \quad (12)$$

where γ is a unknown constant and $v_{n,\,n+1}$ denotes an equivalent (virtual) "symmetrical" noise satisfying

$$|v_{n,\,n+1}| \le \varepsilon \quad (13)$$

in which

$$\varepsilon \le [(1-\underline{\gamma})\theta_{\max} + \bar{\xi}]/2. \quad (14)$$

Since $\underline{\gamma}$ is unknown, the upper bound on ε in (14) will also be unknown.

The features of (12), (13) are illustrated in Fig. 5.

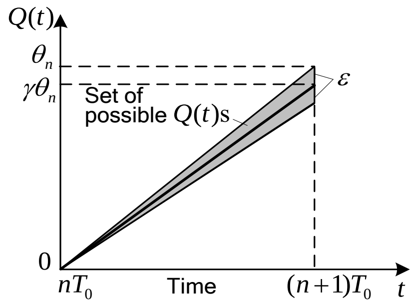

Fig. 5. Interpretation of production processes.

2.3 Control Objective

Introduce the control performance index

$$J = \lim_{n\to\infty} \sup |e_n|, \tag{15}$$

which evaluates the ultimate behaviour of the control system (1) – (7) for all sufficiently large n.

The control aim is to form the reorder policy which yields $\{\theta_n\} := \theta_0, \theta_1, \theta_2, \dots$ minimizing J according to

$$J \to \min_{\{\theta_n\}} \tag{16}$$

provided that the uncertainties of the forms (10), (11) present.

3. PRELIMINARIES

Exploiting the classical control theory, Skurikhin (1972) has established that the simplest order policy defined in (3) leads to appearing the oscillations of the inventory level with the period $T = 2\pi T_0 / \arccos(1/2\sqrt{\gamma})$ meaning that if γ is close to 1, then T is approximately equal to the six planning intervals $(T \approx 6T_0)$.

To suppress the inventory oscillations, a basic decision-making system was improved in Azarskov *et. al.* (2013) by utilizing some result derived from the modern control theory including the robust control and the so-called ℓ_1-optimization. They have established that if γ in (12) is known exactly, then the optimal reorder policy minimizing the performance index J of the form (15) is

$$\theta_n^c = (e_n + \nabla\tilde{Q}[n, n+1] + \nabla\tilde{Q}[n+1, n+2] - \gamma\theta_{n-1}) / \gamma \tag{17}$$

so that the control objective (16) is achieved with $J \le (1-\underline{\gamma})\theta_{\max} + 2\bar{\xi}$ if $\theta_n \equiv \theta_n^c$, and $\nabla\tilde{Q}[n, n+1] \equiv \nabla\tilde{Q}_{n,\,n+1}$, $\nabla\tilde{Q}[n+1, n+2] \equiv \nabla\tilde{Q}_{n+1,\,n+2}$. An advantage of this reorder policy it that $\theta_n \equiv \theta_n^c$ in (2) because it guarantees that the product stock level H_n will not exceed the safety stock level r^0.

Equation (17) describes an improved order policy. To implement this policy, the additional inner feedback and the two-step-ahead predictor are required (see Fig. 6). Unfortunately, the coefficient γ arising in (17) is hard to be derived in a practical application. Thereby the adaptive approach seems to be suitable in order to implement the reorder policy under uncertainty with respect to this coefficient.

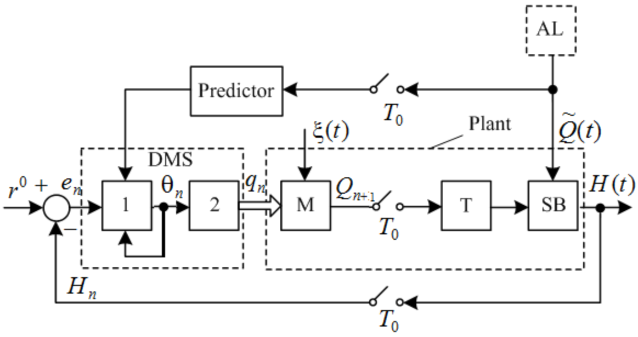

Fig. 6. Block diagram of improved inventory control system.

4. MAIN RESULT

4.1 Adaptive Estimation Algorithm

To deal with unknown γ, the improved inventory control system shown in Fig. 6 needs to be modified by introducing the identifier together with the second additional feedback as depicted in Fig. 7. The inputs of the identifier are the variables θ_n and Q_{n+1} whereas the variable $\gamma(n)$ which is the current estimate of unknown γ in (12) represents its output.

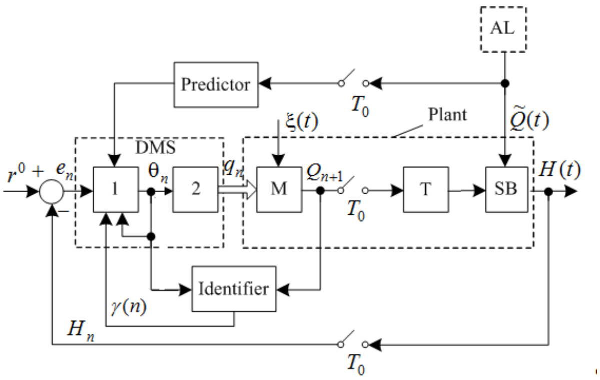

Fig. 7. Block diagram of adaptive inventory control system.

A new adaptive identification algorithm is proposed here for estimating the variable γ under the uncertainty that relates to the bound ε on the absolute values of $v_{n,\,n+1}$ in (13). This algorithm exploits somewhat the adaptive approach advanced by the one of the authors (Zhiteckii, 1996). It is based on combining the point and the set-membership estimations of γ, and is designed via recursive solving the inequalities

$$|\gamma\theta_n - Q_{n+1} - \bar{\xi}/2| \le \varepsilon \quad (n = 0, 1, 2\dots) \tag{18}$$

with respect to the unknown γ and ε. Note that they are directly follow from (12) together with (13).

The inequalities (18) yield

$$(Q_{n+1} - \bar{\xi}/2 - \varepsilon)/\theta_n \le \gamma \le (Q_{n+1} - \bar{\xi}/2 + \varepsilon)/\theta_n ,$$

which can be utilized to produce the set-membership estimation procedure of the form

$$\underline{\gamma}(n+1) = \begin{cases} \underline{\gamma}(n) & \text{for } \underline{\gamma}(n) \ge [Q_{n+1} - \bar{\xi}/2 - \varepsilon(n)]/\theta_n, \\ [Q_{n+1} - \bar{\xi}/2 - \varepsilon(n)]/\theta_n & \text{otherwise,} \end{cases}$$
$$\bar{\gamma}(n+1) = \begin{cases} \bar{\gamma}(n) & \text{for } \bar{\gamma}(n) \le [Q_{n+1} - \bar{\xi}/2 + \varepsilon(n)]/\theta_n, \\ [Q_{n+1} - \bar{\xi}/2 + \varepsilon(n)]/\theta_n & \text{otherwise} \end{cases} \quad (19)$$

if only $\theta_n > 0$ and $\underline{\gamma}(n+1) \le \bar{\gamma}(n+1)$,

and

$$\underline{\gamma}(n+1) = \underline{\gamma}(0), \qquad \bar{\gamma}(n+1) = \bar{\gamma}(0) \qquad (20)$$

if (19) causes $\underline{\gamma}(n+1) > \bar{\gamma}(n+1)$,

where $\underline{\gamma}(n)$ and $\bar{\gamma}(n)$ make sense of *a posteriori* bounds of the intervals to which unknown γ belongs. The variable $\varepsilon(n)$ in (19) represents the current estimate of ε which is generated by the point estimation procedure

$$\varepsilon(n+1) = \begin{cases} \varepsilon(n) & \text{if } \underline{\gamma}(n+1) \le \bar{\gamma}(n+1), \\ \varepsilon(n) + \Delta & \text{otherwise,} \end{cases} \qquad (21)$$

where $\Delta > 0$ is a fixed constant chosen by the designer as some positive number which is small enough.

The point estimation procedure inspired by Zhiteckii (1996) and used for deriving $\gamma(n)$ is

$$\gamma(n+1) = \begin{cases} \gamma(n) & \text{if } |S_n| \le \varepsilon'(n+1), \\ \gamma(n) - [S_n - \varepsilon(n+1)]/\theta_n & \text{if } S_n > \varepsilon'(n+1), \\ \gamma(n) - [S_n + \varepsilon(n+1)]/\theta_n & \text{if } S_n < \varepsilon'(n+1). \end{cases} \quad (22)$$

In these expressions,

$$S_n = \gamma(n)\theta_n - \bar{\xi}/2 - Q_{n+1} \qquad (23)$$

defines the current identification error, and

$$\varepsilon'(n) = \varepsilon(n) + \Delta', \qquad (24)$$

where $\Delta' > 0$ is a sufficiently small positive constant chosen by the designer as in Zhiteckii (1996).

4.2 Adaptive Reorder Policy

The adaptive estimation algorithm (19) to (24) identifying the machine model at each *n*th time instant makes it possible to form the adaptive reorder given by (1), (2) in which

$$\theta_n^c = (e_n + \nabla\tilde{Q}[n, n+1] + \nabla Q[n+1, n+2] - \gamma(n)\theta_{n-1})/\gamma(n) \quad (25)$$

is derived from (17) after replacing γ by $\gamma(n)$.

The important property of the estimation algorithm (19) to (24) caused by (25) in the closed-loop adaptive system is that it converges at a finite step numbers n^* so that

$$\lim_{n\to\infty} \gamma(n) = \gamma_\infty$$

with $\gamma_\infty = \gamma(n^*)$. (Due to space limitation, the proof of this fact is omitted.)

4.3 Simulation Example

To evaluate the adaptive processes caused by (19) to (24) together with the reorder policy (25), two simulation experiments were conducted by taking $r^0 = 40$, $10 \le \nabla Q_{n,\, n+1} \le 20$, and $\gamma_n \in [\underline{\gamma}, \bar{\gamma}]$ with $\underline{\gamma} = 0.7$ and $\bar{\gamma} = 1$. The variables γ_n are generated as the pseudorandom (i.i.d.) sequence in the range [0.7, 1]. In the first experiment simulating the nonadaptive inventory control system with the reorder policy (17), it was put: $\gamma = 1$.

Results of second experiment simulating the adaptive inventory control system with the reorder policy (25) in which $\underline{\gamma}(0) = 0.7$, $\bar{\gamma}(0) = 1$, $\gamma(0) = 1$, $\varepsilon(0) = 1$, and $\Delta = 1$, $\Delta' = 0.0001$ were set, are displayed in Fig. 8.

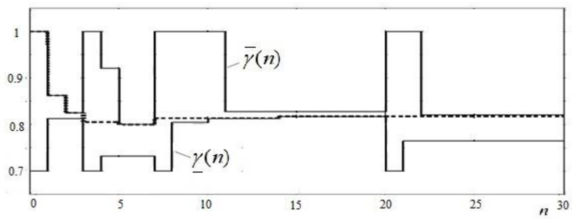

Fig. 8. Adaptive identification processes in second simulation example: current lower and upper bounds on γ (solid lines), and the current estimate $\gamma(n)$ (dashed line).

It can be observed that γ approximately converge to $\gamma_\infty = 0.823$ at the finite step numbers $n^* = 14$. Note that $\gamma(n)$ follows the current upper bound $\bar{\gamma}(n)$ on γ (see Fig. 8).

Fig. 9 presents the dynamical processes in the adaptive and the nonadaptive inventory control systems which have occurred in the two simulation experiments. It shows that the adaptive reorder policy gives the results which is better than in nonadaptive one: the deviation of the product stock level in each *n*th time instant from the safety stock value in the adaptive case is less than when the reorder policy is not updated as in Azarskov *et. al*. (2013). This is an advantage of the proposed approach.

5. CONCLUSION

The proposed approach might be extended on the case where the upper bound on the variable caused by the machine failure is unknown.

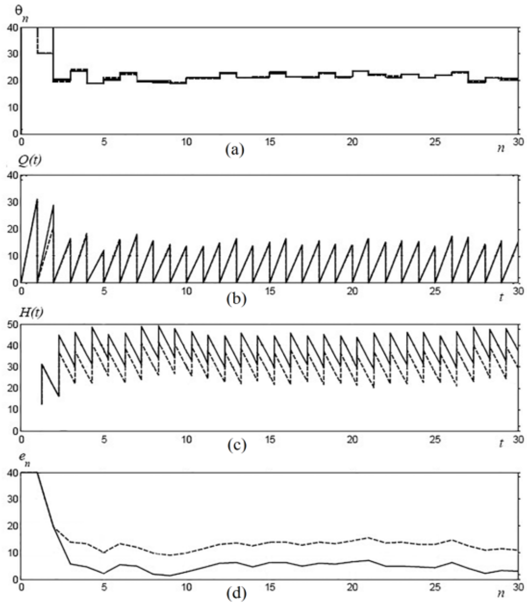

Fig. 9. The performance of the inventory control system after completing the adaptation stage (solid line) and without any adaptation (dashed line): (a) order; (b) production processes; (c) current product stock level; (d) the deviation of product stock level from safety stock value.

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