ORZECHOWSKA Joanna E.[1]
BARTOSZEWICZ Andrzej[2]
BURNHAM Keith J.[3]
PETROVIC Dobrila[4]

Control Theory Applications in Logistics – MPC and other Approaches

Inventory management,
Control theory,
Model predictive control

Abstract

The paper concerns an application of engineering regulation theory concepts to modelling and effective control of logistic systems. Nowadays an achievement of inventory keeping cost vs. benefit trade-off becomes extremely important. This is, however, a complex task with respect to uncertain demand and lead times. These uncertainties result in such problems as high storage costs, varying inventory levels (bullwhip effect) and deterioration of goods. The paper shows a brief review of contributions made in this area of study with special focus on Model Predictive Control.

ZASTOSOWANIE METOD TEORII REGULACJI W LOGISTYCE – PODEJŚCIE KLASYCZNE I STEROWANIE PREDYKCYJNE

Streszczenie

Artykuł przedstawia krótki przegląd zastosowań metod teorii regulacji do modelowania i sterowania systemów logistycznych. Ponieważ osiągnięcie takiego poziomu zapasów, aby zredukować koszty ich magazynowania i jednocześnie zachować ciągłość podaży nie jest zadaniem łatwym, uzasadnione jest stosowanie do tego celu obecnie dobrze rozwiniętych metod teorii sterowania. Artykuł przedstawia zwięzły przegląd literatury dotyczący tej tematyki ze szczególnym uwzględnieniem bardzo skutecznych metod sterowania predykcyjnego.

1. INTRODUCTION

In recent times an importance of well designed logistics operation has increased and the need of logistics systems' continuous improvement appeared. In response to the need many papers have been devoted to this issue and many techniques like convex programming [19], genetic algorithms [39], heuristic methods [37] or simulation [31] have been applied to improve warehouse operation. This paper focuses on engineering control theory application in inventory system modelling, which although is not a new field of research, relatively little researchers dedicated their work to this matter. The control theory, however, offers wide range of mathematical techniques facilitating modelling and control of inventory-production systems, which makes it worth to focus on.

2. LOGISTICS PROBLEM IN CONTROL THEORY DOMAIN

The concept of applying control theory to a logistic system consists of conversion of the problems to the control theory domain, solving it there and then converting it back to the logistics domain. In this section, the approach of mapping an inventory replenishment problem to a control theory framework is considered. To illustrate the mentioned conversion.

Fig. *1* shows an example of the same system presented in two different frameworks namely: operational research and control theory. The same system elements are labeled and understood in different ways in each domain.

Therefore the target inventory level in the control theory domain is understood as a reference signal, the order quantities are modelled as the plant input, the current inventory level represents the system output and is the controlled variable. The lead time (transportation time) is represented as a system time delay, the inventory level fluctuations are understood as system output oscillations, replenishment decision point is considered as a selected controller, while customer demand is considered a system disturbance. Once the logistic system is converted to the control theory framework, several control theory techniques can be applied to control the behaviour of the system in required manner.

[1]Coventry University, Control Theory and Application Centre; Priory Street, Coventry CV1 5FD. E-mail: orzechoj@uni.coventry.ac.uk
[2]Politechnika Łódzka, Instytut Automatyki; 90-924 Łódź, ul. Bohdana Stefanowskiego 18/22. E-mail: andrzej.bartoszewicz@p.lodz.pl
[3]Coventry University, Control Theory and Application Centre; Priory Street, Coventry CV1 5FD. E-mail: csx167@coventry.ac.uk
[4]Coventry University, Control Theory and Application Centre; Priory Street, Coventry CV1 5FD. E-mail: csx200@coventry.ac.uk

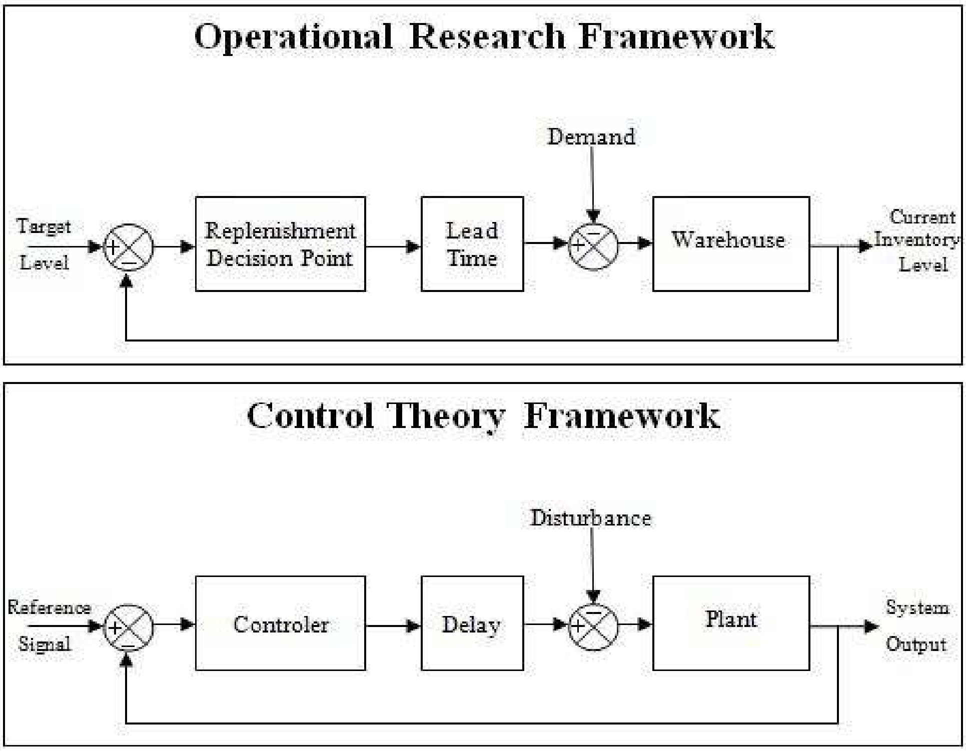

Fig. 1. Conversion of operational research framework to control theory framework

3. CONTROL THEORY METHODS IN LOGISTICS

The origins of application of regulation theory in the field of logistic systems control can be identified in 1950s when Simon [44] applied servomechanism algorithm for supporting replenishment policy in continuous single product inventory control system. The representation of inventory features, like inventory level or order quantity, in a control theory domain, as system's signals, straight away brought a substantial advantage in realistic inventory system modelling. The mentioned advantage was the inventory system modelling with the straightforward consideration of system dynamics. The discrete-time model with application of servomechanism theory was presented by Vassian [47] a few years later. The control engineering attributes, like state space representation of the inventory system, transfer function describing dynamics of the stock levels, reference inventory signal and feedback loop have appeared in the mentioned papers and aimed to support replenishment decisions. This showed the potential power of application of control theory techniques in inventory system modelling.

The next milestone in this field was done by Forrester [20], who paid particular attention to fluctuating behaviour of inventory levels of supply chain's calls, later called bullwhip effect, caused, among others, by lead time lags. Since that time several papers have been contributing to predict, analyse, measure and avoid a bullwhip effect using a control engineering approach. First block diagram representation of inventory and order based production control system (IOBPCS) model and its dynamic analysis was done in early 1980s by Towill [45]. Since that time a target inventory level has been modelled as input to the system and treated as a reference signal, the order quantity has been considered as a manipulated variable and actual inventory level has been considered as an output of the system and treated as a controlled variable. The controlled variable has been fed back. Subsequently such an approach to inventory system modelling was applied by many researchers [2, 3, 7, 22, 23, 24, 26, 42, 43, 48, 50, 51].

The IOBPCS model subsequently was extended and improved by adding more system's components. Besides two already existing block diagram parts, the target inventory level and feedback loop, the lead time delay, demand forecasting policy and work in progress (WIP) feedback loop have appeared. Among IOBPCS contributions we can differentiate continuous and periodic inventory level review approaches [23]. More details about IOBPCS family and IOBPCS' components description have been presented in [33].

Several different control theory attributes which were used to model and analyse inventory-production systems' features can be found in literature over the last decade. Important contribution to this scope of study has been done at Cardiff University with respect to control of bullwhip effect [9, 10, 11, 12, 13, 14, 15, 16, 17, 21, 33, 41, 52]. In considered papers the researchers aimed at smoothing an ordering policy and inventory levels and presented suitability of utilisation of control theory tools in terms of preventing the bullwhip system oscillations.

The example applications of control theory attributed to inventory systems which can be found in literature are as follow. Autoregressive moving average (ARMA) system structure has been used by several researchers for different purposes. Gaalman [22] and Gaalman and Disney [21] hired ARMA system structure to model uncertain component of demand. Aggelogiannaki, Doganis and Sarimveis [1], however, used ARMA structure to model inventory position and recursive least square (RLS) estimation in terms of demand forecasting. State space representation, in turn, has been used for instance by Gaalman [22] for demand modelling, or Rodrigues and Boukas [42] for stock accumulation representation. A simple differential equation has been used by Ignaciuk and Bartoszewicz [26, 28] as a stock balance equation. Transfer function has been commonly applied by different researchers. For instance Dejonckheere et. al. [10, 11] used it for order-up-to policy establishing in respect to bullwhip effect prevention, Hoberg, Bradle and Thonemann [24] formulated transfer function of inventory system for evaluation of ordering signal stability with respect to different lead time delay values, Lin. et al. [36] presented combined closed-loop transfer function representing material balance and information flow of whole supply chain network. The controllability and observability tests of supply chain system can be found in paper of Lalwani, Disney and Towill [33]. Dejonckheere et al. [10, 11] introduced damping factor for smoothing order policy and spectral analysis to obtain demand patterns and frequency response of the sinusoid demand. Gaalman and Disney [21] have applied proportional controller in the inventory feedback loop and described process of tuning it, to prevent bullwhip effect, while Grubbström and Wikner [23] and Samanta and Al-Araimi [43] applied PID controller and combined it with fuzzy logic to maintain the stock at target level. Also estimation techniques can be identified in inventory management literature. The RLS method and Kalman filter, have been used by Aggelogiannaki and Sarimveis [2] and Aggelogiannaki, Doganis and Sarimveis [1] for lead time identification and by Gaalman [22] and Gaalman and Disney [21] for demand forecasting respectively. A contribution to non-zero lead time modelling and compensation in periodic review systems has recently been reported by Ignaciuk and Bartoszewicz in [27, 29, 30]. In these papers the lead time delay has been taken into account in the *n*-th order state matrix and the optimal control action has been found by minimisation of quadratic performance index.

4. MODEL PREDICTIVE APPROACH

Besides classical control techniques, which have been mentioned in previous section, the Model Predictive Control (MPC) has been used as an optimisation tool by several researchers. MPC is a moving horizon control theory technique, aiming at finding a current and future control action in desired optimisation horizon, by on-line optimisation of desired problem. Then the model applies the first control action only. The system dynamics is updated in each sampling instant. Perea-Lopez, Ydstie and Grossmann [40] developed a dynamic decision framework for multi-product, multi-echelon supply chain. The supply chain model includes plant, warehouses, distribution centres and retinal levels. The MPC technique was applied to maximise the profit by reduction of negative impact of unknown demand considered as a system disturbance. The demand prediction is assumed to be known in advance and used by model. Nevertheless, the demand error is regularly updated based on past and current information. Upstream orders are inputs of particular echelon, while shipments represent echelon output. The orders are transferred from upstream echelon to downstream one, while the shipment is moving the opposite direction. Nodes are assumed to handle as many products as the whole system is allowed to handle. The model allows for consideration of many products by splitting each node to one product divisions. The received orders from the downstream nodes are accumulated during the day and shipped the day after, unless the inventory level is too low to satisfy the customer's requirements. Any kind of transportation, like shipment from downstream to upstream nodes, delivery from external suppliers or shipment of goods to the end customers is done at the end of the day when the all day orders are already accumulated. In the model it is represented as additional term which usually is equal to zero besides the circumstances when the time is equal to particular value representing the end of the day. The transportation times and their costs between nodes are known with certainty. The authors consider two different raw materials supply possibilities: the quick response and costly one and the slow response and economic one. The availability of raw sources is assumed to be infinite. The model objective function is related to overall net profit and contains all cost and gross profits in the supply chain related to production process, storage, transportation and sale. In the considered paper two optimal decision making approaches are examined, the centralised and the decentralised one. The results showed that the centralised scenario leads the supply chain overall profit to be higher than is case of decentralised scenario.

Braun et al. [7] developed decision support system for single product, six-node and three-echelon production-inventory system. The discrete MPC aims at finding the optimal order quantities (system input) for reduced inventory levels. The demand (disturbance) prediction is assumed to be known in advance and it is updated based on real demand pattern. The reference signal of the model is assumed to be equal to the predicted demand pattern increased by safety stock level. The estimated order pattern (the predicted system input) is used as a predicted demand pattern (disturbance) for downstream echelon. The actual disturbance is again updated based on current value. Goods posted to customer are understood as system outputs. The authors proposed semi-decentralised decision making system. The separate model predictive controllers are used for each of echelons so that they are shared between nodes included in particular echelon. The forecast information is used by the downstream nodes. The transportation times between nodes are assumed to be known with certainty. The more time consuming routes are chosen only when necessary. It is achieved by setting the target order value as zero and application of different penalties for different ordering routes in case the orders placed for particular route are greater than zero. The daily shipment capacities are constrained as well. The backorders are considered in the model. The time unit in the developed model is equal to one day, which enables modelling of lead time as a system delay. The model has been tested for different knowledge sharing strategies. It was shown that sharing the forecasted demand among all nodes and suppression of real demand pattern is beneficial to the company in respect to achieve smoother order patterns, lower inventory levels and prevent inventory level fluctuations.

Wang, Rivera and Kempf [49] presented effectiveness of MPC algorithm in strategic decision making in semiconductor manufacturing with respect to system sudden changes. In this case the MPC is only an element of comprehensive decision policy for single product, single line and multi echelon manufacturing supply chain, where fluid analogy is applied to illustrate flow of materials. Here work in progress in respect to manufacturing processes is understood as flow of fluid in pipe, while storage areas accumulating goods between manufacturing processes are treated as tanks. In respect to control engineering representation of developed model the inventory levels are understood as a system output and controlled variables, the orders are treated as system first input (manipulated variable) and demand is treated as a second input (disturbance signal). Several constraints, represented as linear equations, are taken into account while optimal decision making. Those are: production and storage capacities, magnitude of starts, inventory levels, manipulated variable constraints, control variable constraints, work in progress capacity. The aim of MPC application in this case is to maintain inventory level at desired set point and satisfy customer's requirements at the same time. Some uncertainties are taken into account in the model like random breakdowns or mistakes of machines which affect the lead time and storage levels. Therefore, the lead time is never known with certainty. To optimise the production scheduling different speeds of assembling machines are considered and used in the model. The demand prediction is used and assumed to be similar to average of real demand pattern. The actual demand is regularly updated.

Tzafestas, Kapsiotis and Kyriannakis [46] presented the MPC application for production planning for multi-product manufacturing system. The aim of the work was to minimise total cost of production and advertising so that the sale and inventory are maintained at desired levels. Sale prices are assumed to be fixed. In this case the production rate and advertising effort are manipulated variables (system inputs) while inventory and sale levels are system outputs (controlled variables). The demand (system disturbance) is controlled by advertising parameter, which allows for demand prediction. The control variables have been constrained in the model. The paper presents the general idea of the developed model only. The applied case study is not explained in details and the structure of studied system is not presented. The simulation results show that after some time the model tunes to achieve satisfying outcomes.

Li and Marlin [35] presented the MPC decision framework for minimisation of total supply chain costs in respect to storage cost, manufacturing cost, transportation cost and penalty backorders cost and at the same time to satisfy customers' requirements. Manufacturing rate, of semi-finished products, plant running time and transportation rates are model manipulated variables. Final product manufacturing rate, lead time and demand are assumed to be uncertain, which require correlated uncertainty description. In simulation two scenarios were examined: the case when demand, lead time and manufacturing rate are predicted correctly and the case when the prediction is not exact. The model performs very well in the first case while in the second case the backorders occur. The reason of this is that the model tends to reduce inventory level to minimise costs and the inventory level is not always enough for the customers' requirements. Consideration of additional safety stock level increased total costs but prevented backorders at the same time.

Aggelogiannaki, Doganis and Sarimveis [1] developed MPC framework for optimisation of order quantities for production system with consideration of system dynamics. Besides unknown demand the model unexpected behaviour is related to machine breakdowns or run out of materials. Adaptive Finite Impulse Response (FIR) model has been applied to approximate the production system's dynamics. The output of FIR system is a production volume while FIR system input is an order quantity. RLS algorithm, as an on-line estimation technique has been used to estimate FIR model coefficients, which are changing over time. Inventory balance equation is represented by autoregressive with exogenous input model (ARX), where demand represents system disturbance, inventory level is system output and controlled variable and orders volume is system input and manipulated variable. The MPC framework employs the objective function which aims at maintaining target inventory level. In the numerical example the authors compare the adaptive MPC framework with Estimated Pipeline Inventory and Order Based Production Control System (EPIOBPCS) of Disney and Towill [15] and with non-adaptive MPC. It was noticed that the adaptive MPC is able to respond faster than EPIOBPCS and also avoids oscillations which occur in case of non-adaptive MPC. Therefore application of adaptive MPC has been justified as an advantage.

5. CONCLUSIONS

The aim of this brief review was to provide the reader with a concise overview of selected applications of control theory methods, in particular model predictive approach to the inventory-production systems. This approach enables to achieve significant improvement of the supply chain performance via application of already existing, well known and usually not very complicated control theory techniques. The modelling of inventory problem in control theory domain enables straightforward consideration of system dynamics and uncertainties. As a consequence the contribution done in application of control theory to inventory modelling constitute an advantage in developing more realistic tools in inventory optimisation over the contribution in application of common and untaught static optimisation techniques [6, 38, 18, 34, 8, 25, 32, 4, 5]. The application of systematically designed control action in replenishment system is still not very common and still not many researchers devoted their work to this matter. Therefore there is still a sufficient room for future improvements.

ACKNOWLEDGEMENT

This work has been financed by the Polish State budget in the years 2010–2012 as a research project N N514 108638 "Application of regulation theory methods to the control of logistic processes".

6. REFERENCES

[1] Aggelogiannaki, E., Doganis, P. & Sarimveis, H., 2008. An adaptive model predictive control configuration for production-inventory systems. *International Journal of Production Economics*, 114(1), 165-178.

[2] Aggelogiannaki, E. & Sarimveis, H., 2008. Design of a novel adaptive inventory control system based on the online identification of lead time. *International Journal of Production Economics*, 114(2), 781-792.

[3] Agrell, P. J. & Wikner, J. 1996. An MCDM framework for dynamic systems. *International Journal of Production Economics*, 45(1-3), 279-292.

[4] Ahmadi, Javid & Azad, N., 2010. Incorporating location, routing and inventory decisions in supply chain network design. *Transportation Research Part E: Logistics and Transportation Review*, 46(5), 582-597.

[5] Avinadav, T.& Arponen, T., 2009. An EOQ model for items with a fixed shelf-life and a declining demand rate based on time-to-expiry. *Journal of Operational Research*, 26(6), 759-767.

[6] Baumol, W.J. & Vinod, H.D.,1970. An inventory theoretic model of freight transport demand, *Management Science*, 16, 413–421.

[7] Braun, M., Rivera E.D., Flores, M.E., Carlyle, W.M. & Kempf, K.G., 2003. A model predictive control framework for robust management of multi-product, multi-echelon demand networks. *Annual Reviews in Control*, 27(2), 229.

[8] Chung , K. J. & Liao, J.J., 2009. The optimal ordering policy of the EOQ model under trade credit depending on the ordering quantity from the DCF approach. *European Journal of Operational Research*, 196 (2), 563-568.

[9] Dejonckheere, J., Disney, S.M., Lambrecht, M.R. & Towill, D.R. 2002. Transfer function analysis of forecasting induced bullwhip in supply chains. *International Journal of Production Economics*, 78(2), 133-144.

[10] Dejonckheere, J., Disney, S.M., Lambrecht, M.R. & Towill, D.R. 2003. Measuring and avoiding the bullwhip effect: a control theoretic approach. *European Journal of Operational Research*, 147(3), 657-590.

[11] Dejonckheere, J., Disney, S.M., Lambrecht, M.R. & Towill, D.R. 2004. The impact of information on the bullwhip effect in supply chains: a control engineering perspective. *European Journal of Operational Research*, 153(3), 727-750.

[12] Disney, S.M. & Towill, D.R., 1996. Industrial dynamics modelling of supply chains. *International Journal of Physical Distribution & Logistics Management*, 26 (2), 23-42.

[13] Disney, S.M. & Towill, D.R., 2002. A discrete transfer function model to determine the dynamic stability of a vendor management inventory supply chain, *Industrial Journal of Production Research*, 40 (1), 179-204.

[14] Disney, S.M. & Towill, D.R. 2003a. Vendor-managed inventory and bullwhip reduction in a two-level supply chain. *International Journal of Operation and Production Management*, 23(6), 625-651.

[15] Disney, S.M. & Towill, D.R., 2003b. On the bullwhip and inventory variance produced by an ordering policy, *OMEGA: The International Journal of Management Science*, 31 (3), 157-167.

[16] Disney, S.M. & Towill, D.R. 2005. Elimination drift in inventory and order based production control systems. *International Journal of Production Economics*, 93-94(8), 331-344.

[17] Disney, S.M. & Towill, D.R., 2006. A methodology for benchmarking replenishment-induced bullwhip, *An International Journal of Supply Chain Management*, 11 (2), 160-168.

[18] Ehrhardt, R.,1997. A model of JIT make-to-stock inventory with stochastic demand. *Journal of the Operational Research Society*, 48 (10), 1013-1020.

[19] Feng, Y. et al., 2011. Solving single-product economic lot-sizing problem with non-increasing setup cost, constant capacity and convex inventory cost in O(N log N) time. *Computers & Operations Research*, 38(4), 717-722.

[20] Forrester, J., 1958. Industrial dynamics, a major breakthrough for decision makers, *Harvard Business Review*, July–August, 36(4), 37–66.

[21] Gaalman, G. & Disney, S.M., 2006. State space investigation of the bullwhip problem with ARMA(1,1) demand processes. *International Journal of Production Economics*, 104(2), 327-339.

[22] Gaalman, G., 2006. Bullwhip reduction for ARMA demand: the proportional order-up-to policy versus the full-state-feedback policy. *Automatica*, 42(8), 1283-1290.

[23] Grubbström, R.W. & Wikner, J., 1996. Inventory trigger control policies developed in terms of control theory. *International Journal of Production Economics*, 45(1-3), 397-406.

[24] Hoberg, K., Bradley, J.R. & Thonemann, U.W., 2007. Analyzing the effect of the inventory policy on order and inventory variability with linear control theory. *European Journal of Operational Research*, 176(3), 1620-1642.

[25] Hsu K. & Wen-Kai, 2009. EOQ Model for imperfective items under a one-time-only discount. *Omega* 37(5), 1018-1026.

[26] Ignaciuk, P. & Bartoszewicz, A., 2011. Dead-time compensation in continuous-review perishable inventory systems with a remote supply source. *Archives of Control Sciences*, 21(1), 5-28.

[27] Ignaciuk, P. & Bartoszewicz, A., 2010a. Linear-quadratic optimal control strategy for periodic-review inventory systems. *Automatica*, 46(12), 1982-1993.

[28] Ignaciuk, P. & Bartoszewicz, A., 2010b. Smith predictor based control of continuous-review perishable inventory systems with a single supply source. *8th European Workshop on Advanced Control and Diagnosis*.

[29] Ignaciuk, P. & Bartoszewicz, A., 2010c. LQ optimal sliding mode supply policy for periodic inventory systems. *IEEE Transactions on Automatic Control*, 55(1), 269-274

[30] Ignaciuk, P. & Bartoszewicz A., 2010d. An inventory management in periodic-review systems with multiple capacitated suppliers and batch ordering. in Applications of Systems Science, Exit Publishing House, Warszawa, 307-314.

[31] Köchel, P. & Nieländer, U., 2005. Simulation-based optimisation of multi-echelon inventory systems. *International Journal of Production Economics*, 93-94, pp. 505-513.
[32] Konstantaras, I. and Skouri, K., 2010. Lot sizing for a single product recovery system with variable setup numbers. *European Journal of Operational Research*, 203(2), 326-335.
[33] Lalwani, C.S., Disney, S.M. & Towill, D.R., 2006. Controllable, observable and stable state space representations of a generalized order-up-to policy. *International Journal of Production Economics*, 101(1), 172-184.
[34] Li, J., Edwin Cheng, T. and Wang, S., 2007. Analysis of postponement strategy for perishable items by EOQ-based models. *International Journal of Production Economics*, 107(1), 31-38.
[35] Li, X. & Marlin, T.E., 2009. Robust supply chain performance via Model Predictive Control. *Computers & Chemical Engineering*, 33(12), 2134-2143.
[36] Lin, P.-H., Wong, D.S.-H., Jang, S.-S., Shieh, S.-S. & Chu, J.-Z., 2004. Controller design and reduction of bullwhip for a model supply chain system using Z-transform analysis. *Journal of Process Control*, 14(5), 487-499.
[37] Liu, S.-C. & Chen, J.-R., 2011. A heuristic method for the inventory routing and pricing problem in a supply chain. *Expert Systems with Applications*, 38(3), pp. 1447-1456.
[38] Mariani, L. & Nicoletti, B., 1973. Optimization of deterministic, multiproduct inventory model with joint replenishment. *Management Science*, 20(3), 349-362.
[39] Pasandideh, S.H.R., Niaki, S.T.A. & Nia, A.R., 2011. A genetic algorithm for vendor managed inventory control system of multi-product multi-constraint economic order quantity model. *Expert Systems with Applications*, 38(3), 2708-2716.
[40] Perea-Lopez, E., Ydstie, B.E. & Grossmann, I.E. 2003. A model predictive control strategy for supply chain optimisation. *Computers & Chemical Engineering*, 27(8/9), 1201-1218.
[41] Potter, A., Towill, D.R., Bohme, T. & Disney, S.M., 2009. The influence of multi-product production strategy on factory induced bullwhip. *International Journal of Production Research*, 47(20), 5739-5759.
[42] Rodrigues, L. & Boukas, E. K., 2006. Piecewise-linear H∞ controller synthesis with application to inventory control of switched production systems. *Automatica*, 42(1), 1245-1254.
[43] Samanta, B. & Al-Araimi, S.A., 2001. An inventory control model using fuzzy logic. *International Journal of Production Economics*, 73(3), 217-226.
[44] Simon, H.A., 1952. On the application of servomechanism theory in the study of production control. *Econometrica*, 20(2), 247–268.
[45] Towill, D.R. 1982. Dynamic analysis of an inventory and order based production control system. *International Journal of Production Research*, 20(6), 671-687.
[46] Tzafestas, S., Kapsiotis, G. & Kyriannakis, E., 1997. Model-based predictive control for generalized production planning problems. *Computers in Industry*, 34(2), 201-210.
[47] Vassian, H.J, 1954. Application of discrete variable servo theory to inventory control. *Arthur D. Little, Inc., Cambridge Massachusetts.*
[48] Venkateswaran, J. & Son, Y.-J., 2006. Effect of information update frequency on the stability of production–inventory control systems *International Journal of Production Economics*, 106 (1), 171-190
[49] Wang, W., Rivera, D.E. & Kempf, K.G., 2007. Model predictive control strategies for supply chain management in semiconductor manufacturing. *International Journal of Production Economics*, 107(1), 56-77.
[50] Wikner, J., Towill, D.R. & Naim, M., 1991. Smoothing supply chain dynamics. *International Journal of Production Economics*, 22(3), 231-248.
[51] Zafra-Cabeza, A., Ridao, D.E., Camacho, E.F., Kempf, K.G, & Rivera, D.E., 2007, Managing risk in semiconductor manufacturing: A stochastic predictive control approach. *Control Engineering Practice*, 15(8), 969-984.
[52] Zhou, L., Disney S. & Towill, D.R., 2010. A pragmatic approach to the design of bullwhip controllers. *International Journal of Production Economics*, 128(2), 556-568.