Journal of Theoretical and Applied Information Technology
31st December 2020. Vol.98. No 24
© 2005 – ongoing JATIT & LLS

ISSN: **1992-8645** www.jatit.org E-ISSN: **1817-3195**

PLANNING AND INVENTORY CONTROL BASED ON IDENTFICATION SYSTEM AND PID/ LQR CONTROLLER

HICHAM SARIR
National School of Applied Sciences (ENSA)
Tetouan, Morocco
E-mail: hsarrir@uae.ac.ma

ABSTRACT

This article deals with development of an intelligent production and inventory control of an aerospace assembly line. The proposed architecture is based on control laws in automatic control systems field. The first step is to identify the transfer function linked input raw material flow and output flow of assembly line by using MATLAB System Identification Toolbox. The second step is to design the appropriate planning and control model. In fact two models are proposed and compared: The first model is based on PID controller and the second one is based on LQR controller. A real data of Moroccan aerospace line assembly is used to illustrate the feasibility of the proposed methodology. Simulation results confirm that the model based on LQR controller gives better performance than PID controller.

Keywords: *Transfer function, PID controller, LQR controller, MATLAB System Identification Toolbox.*

1. INTRODUCTION

In the recent decades, the industrial companies are facing major changes in their external environment such the global competition, market volatility and uncertain customer demand. In addition, they are facing various internal constraints such machines breakdowns, absenteeism, quality problem over-inventory…etc.

The companies need a robust planning and control system that make best decisions to find a compromise between the three conflicting objectives: reducing WIP (Work In Progress) and inventories, increasing customer satisfaction and increasing return on investment as well. Several approaches, methods and tools have been proposed or used, like DDMRP (Demand Driven Material Requirement Planning) ([1],[2]), MRP (Material Requirement Planning) [3] and MRPII (Material Resource Planning)), JIT (Just In Time) [4], TOC (theory of constraints)[5],[6], OPT (Optimized Production Technology), ERP (Enterprise Resource Planning) [7],[8],[9], APS (Advanced Planning and Scheduling) **Error! Reference source not found.**,…etc. The common point of these tools is to control the production flow.

According to the literature, several researches deal with the modeling of the planning and control system [11] present a conceptual model, a use-case matrix and a product–process framework for a smart production planning and control (smart PPC) system and illustrates the use of these artefacts through four case companies. The presented model adopts an incremental approach that companies with limited resources could employ in improving their PPC process in the context of industry 4.0 and sustainability. Wang and al [12] proposed an optimization model based on multi-objective production planning. The optimized objectives are on-time delivery, balanced production, inventory, overtime production and other management objectives in the production progress and through setting cost parameters for all kinds of production objectives to maintain the balances among the multiple objectives.

Grabot B and al [13], interpret the role of production control by the regulation of the flows that includes all activities for production in the short term. Also in accordance with the objectives set by the production management in the case of action of the pilot is to adapt production to unforeseen events that may occur at the operational by changing some variables (scheduling, capacity management, subcontracting, etc.). Porter and al [14] were designing production control strategy that based on a fuzzy-logic controller to minimize both WIP (Work In Progress) and production surplus, but under the (unrealistic) assumption that machines do not fail.

Tamani and al [15] proposed a production-flow control methodology based on arithmetic fuzzy interval to build a decision according to the satisfaction degree of the conflicting objectives quantified by fuzzy intervals. Sheldon and al [16] presented the control rules for job shop scheduling based on the Flow Rate Control approach, stochastic control theory and dynamic programming algorithms for a system consisting of unreliable machines and finite buffers. Kimemia and al and [17] and Gershwin and [18] proposed a feedback control policy of continuous production flow based on solving a stochastic optimal control problem.

Santiago and al [19] proposed a new methodology to obtain a reorder policy for inventory system. This methodology based on APIOBPCS control (automatic pipeline feedback order-based production control system), PID and Extended Kalman Filter (EKF) scheme was presented.

Daniel al [20], introduced PID-controller based decision policy to manage a single inventory in a supply chain. The goals were to illustrate to first-year students the usefulness of an engineering-based approach in a non-traditional application such as supply chain management. A comparison with EOQ-based approaches shows that a well-tuned PID policy can reduce variability in the supply chain, leading to reduce the need for safety stock, to lower incidence of backorders, and mitigation of the “bullwhip effect”.Accomplishing these goals in an actively managed supply chain is ultimately beneficial for the financial well-being of the enterprise.

In this paper, also we introduce strategy field of automatic domain to develop an intelligent production and inventory control of real manufacturing system. This strategy is organized on two steps: The first step consists of identified the linearized transfer function for the studied system. In this step too we used MATLAB identification toolbox system to identify the best model with the best fit. In the second step we identify the appropriate planning and control system for the transfer function estimated. In our study we introduce PID controller (Proportional Integral Derivative) [21] and LQR controller (Linear Quadratic Regulator) [22] to design the planning and control system. PID controller is a generic mechanism control used in industrial control systems; it calculates the difference between the setpoint value and the measurement output, which is known as a system error. The goal is to minimize this error by having a feedback system to compensate for the difference between the desired setpoint and measured output. LQR is an optimal controller, which covers the operation of a dynamic system at minimum cost. Generally, the dynamics of the system is expressed by a set of linear differential equations, while the cost is defined by a quadratic function, known as a problem LQ [23] .The term "cost" is many times described as a sum of the deviations of key measurements of desired values. Consequently, the characteristic of this algorithm is to adjust the setting of the controller of the algorithm and to ensure that undesirable gaps are minimized. This strategy is finally tested and validate on an aerospace assembly line in Moroccan Company.

The goal of this article is proposes a comprehensive model that gives best fit of real system. To achieve that, below hypotheses are discussed:

Hypothesis 1: The data of input and output flow are available measurable and reliable.

Hypothesis 2: The transfer function of studied can be identified.

The organization of the paper is as follows: Section 2 is devoted to formulate the proposed methodology of design planning and inventory control on detail. Section 3 illustrates the application of this methodology on an assembly line of aerospace company. In this section, simulation tests and their results are presented. Section 4 illustrates the result of the comparative performance between PID and LQR controller. LQR has demonstrated in our study more advantages than PID. Finally, concluding remarks and future works are presented by Section 5.

2. PLANNING AND CONTROL MODEL

In this section, the basic idea is to design the production and control system of an aerospace line assembly (real system) figure 1. First, MATLAB System Identification Toolbox ([23], [24], [25]) is used to build a transfer function from input-output data of the assembly line studied. Secondly, the controller is designed from the transfer function.

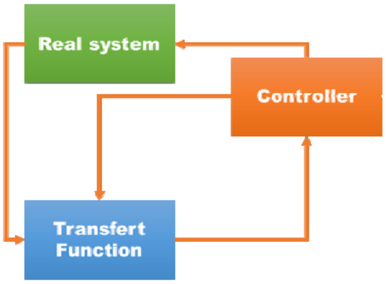


Figure 1: System design of control and inventory management

Figure 2 explain in detail the steps of the planning and control design:

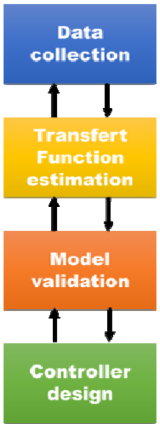


Figure 2: Procedure design controller

2.1 Data collection

The identification process is the acquisition of data. This step is very important and generally consumes a lot of time.

Depending on the nature of the system under study, collection of data and/or information may be technically achieved in different ways:

- By direct input/ output measurements on shop floor
- By using the ERP data
- By experimental design

2.2 Transfer function estimation

Transfer function models describe the relationship between the inputs and outputs of a system using a ratio of polynomials. In our study, we have a single-input/single-output (SISO) model. The input is raw material and the output is final product.

$$Y(s) = \frac{num(s)}{den(s)} e^{-\tau s} U(s) + E(s) \qquad (1)$$

Where, Y(s), U(s) and E(s) represent the Laplace transforms of the output, input and noise, respectively. num(s) and den(s) represent the numerator and denominator polynomials that define the relationship between the input and the output. Where τ represents the delay.

2.3 Model validation:

Model validation is the process that checks the suitability of the model. After describing the model of the system studied, the validation process checks whether the model reproduces the behavior of the system within acceptable limits. Iterate between refinement and validation of the model until you find the simplest model that captures the best system dynamics. In our study, we use the model-output plot to check how well the model output matches the measured output in the validation data set.

2.3 Controller design:

In this section, two controllers' schemes (LQR and PID) are proposed and described in detail.

2.3.1 PID Controller:

PID controller is widely used in industrial control application because of their structural simplicity, reputation, robust performance, and easy implementation. The PID consist on three components: proportional, integral and derivative component. The three controller components can be chosen based on one's experience or through some simple selection methods such as the classical tuning rules proposed by Ziegler-Nichols.

In this method the parameters of the PID controller can be determined graphically by finding out some parameters based on step response or experimentally by finding out the critical gain and critical frequency of the proportional controller

In our study, we use PID controller to design an overall control of the line assembly. Any change on output rate flow of the production system will act directly on the supply of raw material rate flow. The advantage of this type control strategy that is gives a centralized control; it treats the system as a whole. Figure 3 shows the diagram of assembly line with PID controller

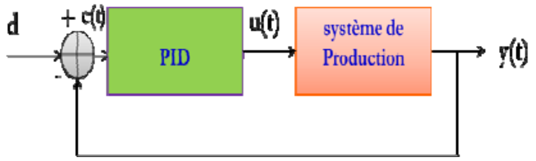


Figure 3. Planning and inventory control based on PID controller

A PID (proportional controller, integrator and differentiator) generates the control *u(t)* from the deviation *e(t)* between the stepoint and the measured output *y(t)*. The control signal is a sum of three terms: the P-term (which is proportional to the error), the I-term (which is proportional to the integral of the error), and the D-term (which is proportional to the derivative of the error). The controller parameters are proportional gain K_p, integral gain K_i and derivative gain K_d.

$$e(t) = d - y(t) \qquad (2)$$

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{\partial e(t)}{\partial t} \qquad (3)$$

Its transmittance of Laplace is:

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \qquad (4)$$

- Ziegler Nichols PID Tuning:

The Ziegler Nichols is a heuristic method of tuning PID controller. This technique proposed the rules for tuning the controller and finding the three values (KP, KI and KD) based on transient step response of the plant [27]. Graphically this technique consist first on identified two constants delay time (L) and time constant (T) [28] by drawing a tangent on the point of inflection of the curve and then finding the intersections of the tangent line with the steady state line and the time axis as shown in figure 4.3. Secondly, set the values of each components of PID controller according to the formula given in the table 1.

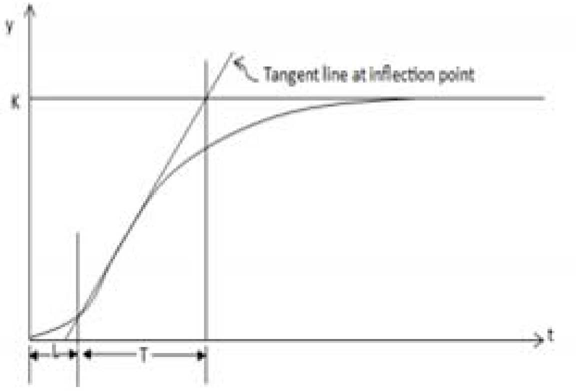


Figure 3 Response curve for Ziegler Nichols method [27]

Table 1: Formula to determine PID controller parameters according to Ziegler-Nichols step response method

Type	*Controller parameters*		
	K_p	Ki	K_d
P	T/L	0	0
PI	0.9*T/L	L/0.3	0
PID	1.2*T/	2*L	0.5*L

2.3.2 LQR Controller:

Linear Quadratic Regulator (LQR) is one of the state space based optimal control method. The system can be stabilized using full state feedback. The schematic of this type of control system is shown in Figure 4.

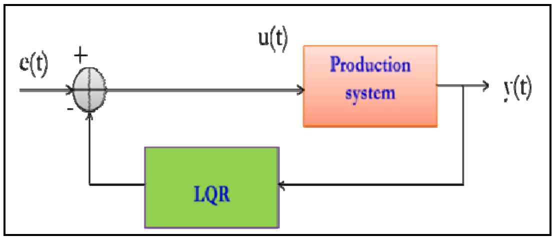


Figure 4. Planning and inventory control based on LQR controller

The state and output matrix formula describing the Production system can be written as the following equation:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \quad (5)$$

We use an optimal control that minimizes the quadratic function cost:

$$J_{LQR} = \int_0^{t} z(t)Qz(t) + \rho u(t)Ru(t)dt \quad (6)$$

Where, Q and R are weighting matrices and should be positive-semi-definite and positive definite, respectively. Since system is controllable, the method which is able to minimize J_{LQR} is called LQR. Considering the functional (2) in LQR the following RICCATI equation should be solved:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (7)$$

By solving the above RICATTI equation the positive-definite matrix P is obtained, thus the optimal gain and controller are calculated as:

$$K_{LQR} = R^{-1}B^T P \quad (8)$$

$$u(t) = -K_{LQR}x(t) \quad (9)$$

Therefore, the closed-loop poles are the eigenvalues of $A - BK_{lqr}$.

$$\dot{x}(t) = (A - BK_{LQR})x(t) \quad (10)$$

$$\dot{x}(t) = A_1 x(t) \quad (11)$$

With A_1 the closed-loop plant matrix.

3. SIMULATION :

In order to evaluate performances of the proposed method, we refer to data of an assembly line on Moroccan aerospace company. The line is consisted of seven workstations successively {W1, W2, W3, W4, W5, W6, W7} as shown on figure 5. u(t) represent de the input flow (raw material) and y(t) represent the output flow (final product). The goal of planning and control system is to meet customer needs while reducing WIP.

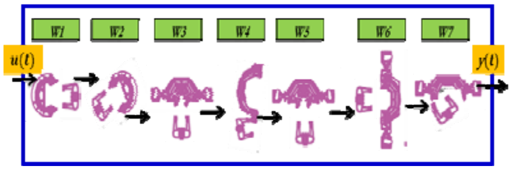


Figure 5. An assembly line of aerospace company

The inputs and outputs data of assembly line are collected from the ERP of the company and loaded in MATLAB work space. The figure 6 shown the history of the input u(t) and output y(t).

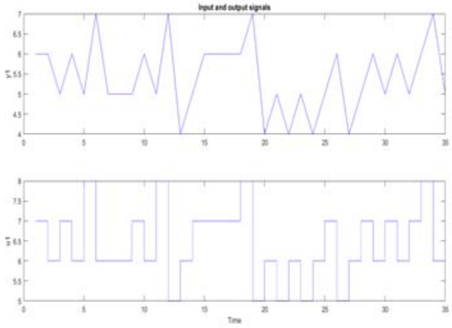


Figure 6. Input and Output measured of the line assembly

MATLAB system identification toolbox is used to estimate the transfer function .We open the system identification tool box (‘ident’) and import u(t) and y(t) data. The identification window and process model window are shown in figure 7.

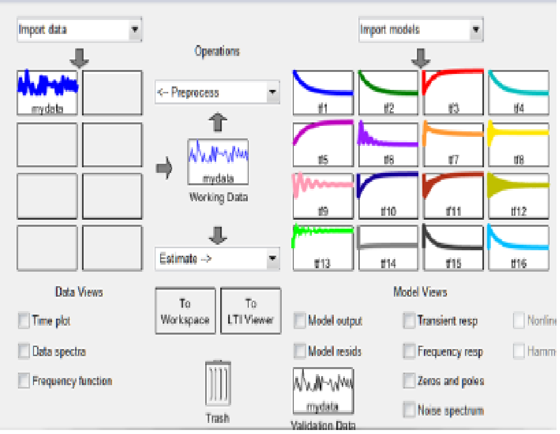


Figure 7. Identification window of MATLAB toolbox

Multiple simulation are done to get the best transfer function estimation by using different combination of zeros, pole and delay.

30 Simulations are done Figure 8 shown the output simulation of 10 transfer functions estimated and their best fit value.

Table 2 represents the transfer functions results of the best 17 simulations. The best fitness Colum represents the capacity of each transfer function to obtain the same behaviors than the real system. According to the best fit value, G1 represent the best model.

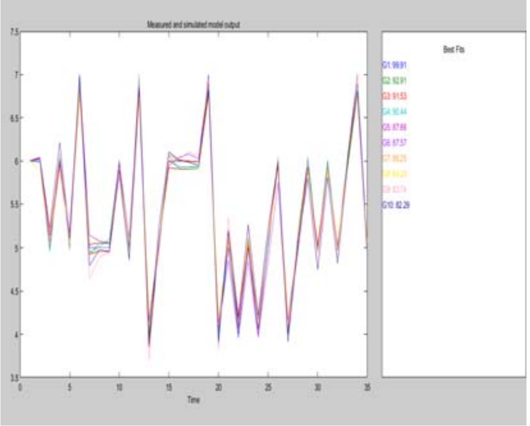
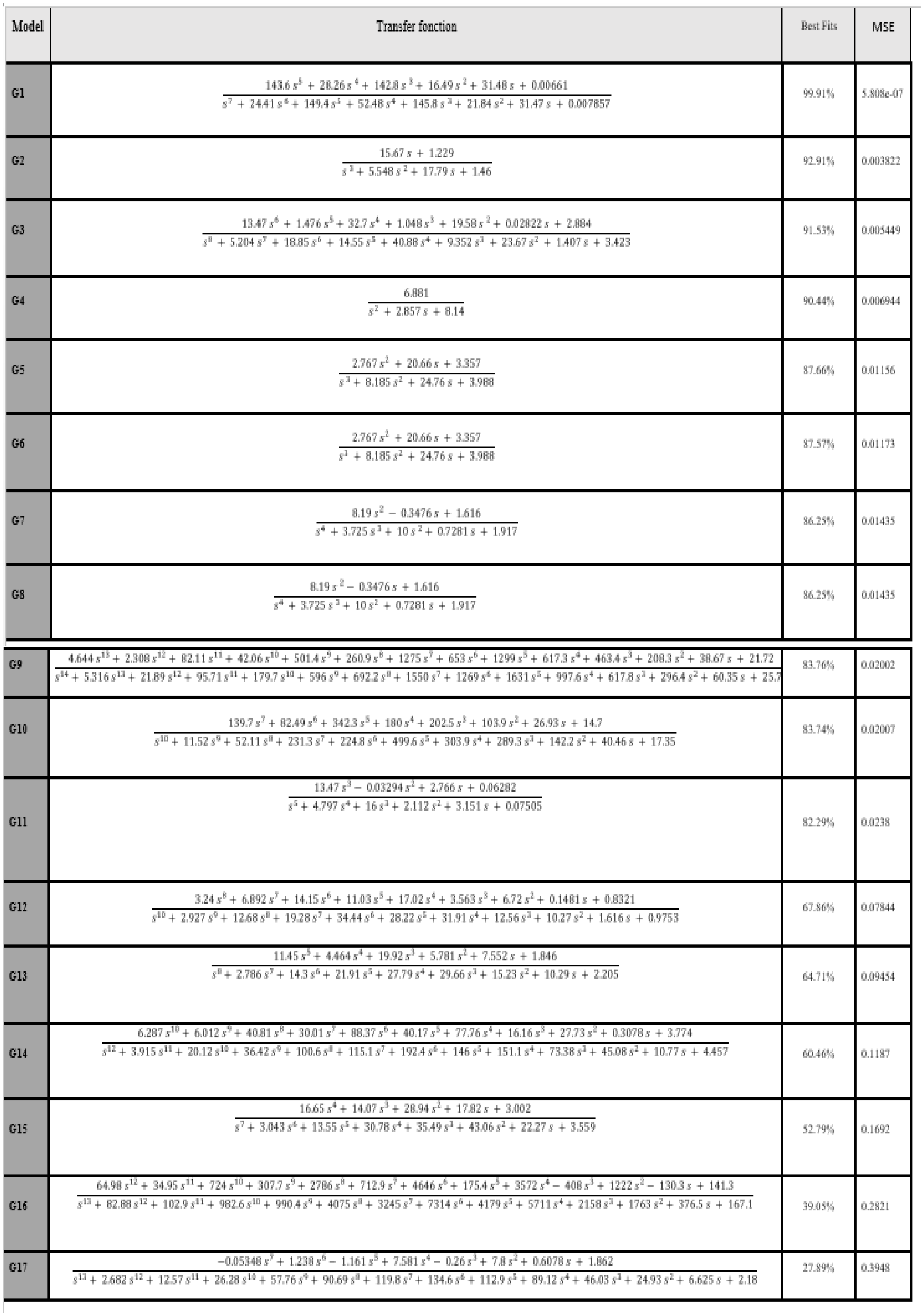


Figure 8. Output simulation of transfer function estimated and their best fits value

Table 2: Transfer function estimated of aerospace line assembly



Model	Transfer fonction	Best Fits	MSE
G1	$\frac{143.6\,s^5 + 28.26\,s^4 + 142.8\,s^3 + 16.49\,s^2 + 31.48\,s + 0.00661}{s^7 + 24.41\,s^6 + 149.4\,s^5 + 52.48\,s^4 + 145.8\,s^3 + 21.84\,s^2 + 31.47\,s + 0.007857}$	99.91%	5.808e-07
G2	$\frac{15.67\,s + 1.229}{s^3 + 5.548\,s^2 + 17.79\,s + 1.46}$	92.91%	0.003822
G3	$\frac{13.47\,s^6 + 1.476\,s^5 + 32.7\,s^4 + 1.048\,s^3 + 19.58\,s^2 + 0.02822\,s + 2.884}{s^8 + 5.204\,s^7 + 18.85\,s^6 + 14.55\,s^5 + 40.88\,s^4 + 9.352\,s^3 + 23.67\,s^2 + 1.407\,s + 3.423}$	91.53%	0.005449
G4	$\frac{6.881}{s^2 + 2.857\,s + 8.14}$	90.44%	0.006944
G5	$\frac{2.767\,s^2 + 20.66\,s + 3.357}{s^3 + 8.185\,s^2 + 24.76\,s + 3.988}$	87.66%	0.01156
G6	$\frac{2.767\,s^2 + 20.66\,s + 3.357}{s^3 + 8.185\,s^2 + 24.76\,s + 3.988}$	87.57%	0.01173
G7	$\frac{8.19\,s^2 - 0.3476\,s + 1.616}{s^4 + 3.725\,s^3 + 10\,s^2 + 0.7281\,s + 1.917}$	86.25%	0.01435
G8	$\frac{8.19\,s^2 - 0.3476\,s + 1.616}{s^4 + 3.725\,s^3 + 10\,s^2 + 0.7281\,s + 1.917}$	86.25%	0.01435
G9	$\frac{4.644\,s^{13} + 2.308\,s^{12} + 82.11\,s^{11} + 42.06\,s^{10} + 501.4\,s^9 + 260.9\,s^8 + 1275\,s^7 + 653\,s^6 + 1299\,s^5 + 617.3\,s^4 + 463.4\,s^3 + 208.3\,s^2 + 38.67\,s + 21.72}{s^{14} + 5.316\,s^{13} + 21.89\,s^{12} + 95.71\,s^{11} + 179.7\,s^{10} + 596\,s^9 + 692.2\,s^8 + 1550\,s^7 + 1269\,s^6 + 1631\,s^5 + 997.6\,s^4 + 617.8\,s^3 + 296.4\,s^2 + 60.35\,s + 25.7}$	83.76%	0.02002
G10	$\frac{139.7\,s^7 + 82.49\,s^6 + 342.3\,s^5 + 180\,s^4 + 202.5\,s^3 + 103.9\,s^2 + 26.93\,s + 14.7}{s^{10} + 11.52\,s^9 + 52.11\,s^8 + 231.3\,s^7 + 224.8\,s^6 + 499.6\,s^5 + 303.9\,s^4 + 289.3\,s^3 + 142.2\,s^2 + 40.46\,s + 17.35}$	83.74%	0.02007
G11	$\frac{13.47\,s^3 - 0.03294\,s^2 + 2.766\,s + 0.06282}{s^5 + 4.797\,s^4 + 16\,s^3 + 2.112\,s^2 + 3.151\,s + 0.07505}$	82.29%	0.0238
G12	$\frac{3.24\,s^8 + 6.892\,s^7 + 14.15\,s^6 + 11.03\,s^5 + 17.02\,s^4 + 3.563\,s^3 + 6.72\,s^2 + 0.1481\,s + 0.8321}{s^{10} + 2.927\,s^9 + 12.68\,s^8 + 19.28\,s^7 + 34.44\,s^6 + 28.22\,s^5 + 31.91\,s^4 + 12.56\,s^3 + 10.27\,s^2 + 1.616\,s + 0.9753}$	67.86%	0.07844
G13	$\frac{11.45\,s^5 + 4.464\,s^4 + 19.92\,s^3 + 5.781\,s^2 + 7.552\,s + 1.846}{s^8 + 2.786\,s^7 + 14.3\,s^6 + 21.91\,s^5 + 27.79\,s^4 + 29.66\,s^3 + 15.23\,s^2 + 10.29\,s + 2.205}$	64.71%	0.09454
G14	$\frac{6.287\,s^{10} + 6.012\,s^9 + 40.81\,s^8 + 30.01\,s^7 + 88.37\,s^6 + 40.17\,s^5 + 77.76\,s^4 + 16.16\,s^3 + 27.73\,s^2 + 0.3078\,s + 3.774}{s^{12} + 3.915\,s^{11} + 20.12\,s^{10} + 36.42\,s^9 + 100.6\,s^8 + 115.1\,s^7 + 192.4\,s^6 + 146\,s^5 + 151.1\,s^4 + 73.38\,s^3 + 45.08\,s^2 + 10.77\,s + 4.457}$	60.46%	0.1187
G15	$\frac{16.65\,s^4 + 14.07\,s^3 + 28.94\,s^2 + 17.82\,s + 3.002}{s^7 + 3.043\,s^6 + 13.55\,s^5 + 30.78\,s^4 + 35.49\,s^3 + 43.06\,s^2 + 22.27\,s + 3.559}$	52.79%	0.1692
G16	$\frac{64.98\,s^{12} + 34.95\,s^{11} + 724\,s^{10} + 307.7\,s^9 + 2786\,s^8 + 712.9\,s^7 + 4646\,s^6 + 175.4\,s^5 + 3572\,s^4 - 408\,s^3 + 1222\,s^2 - 130.3\,s + 141.3}{s^{13} + 82.88\,s^{12} + 102.9\,s^{11} + 982.6\,s^{10} + 990.4\,s^9 + 4075\,s^8 + 3245\,s^7 + 7314\,s^6 + 4179\,s^5 + 5711\,s^4 + 2158\,s^3 + 1763\,s^2 + 376.5\,s + 167.1}$	39.05%	0.2821
G17	$\frac{-0.05348\,s^7 + 1.238\,s^6 - 1.161\,s^5 + 7.581\,s^4 - 0.26\,s^3 + 7.8\,s^2 + 0.6078\,s + 1.862}{s^{13} + 2.682\,s^{12} + 12.57\,s^{11} + 26.28\,s^{10} + 57.76\,s^9 + 90.69\,s^8 + 119.8\,s^7 + 134.6\,s^6 + 112.9\,s^5 + 89.12\,s^4 + 46.03\,s^3 + 24.93\,s^2 + 6.625\,s + 2.18}$	27.89%	0.3948

3.2 PID controller:

According to step response of line assembly (figure 9) and Ziegler Nichols method, Table 3 represent the PID controller tuning parameters.

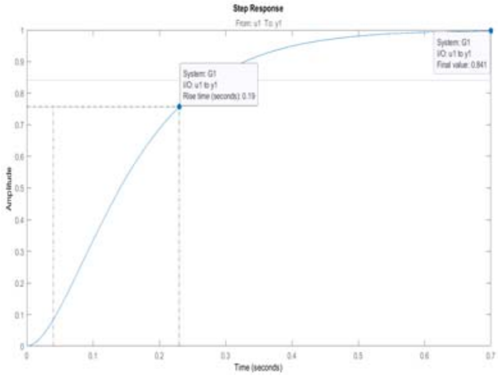


Figure 9: Step response of transfer function G1

Table 3. PID controller parameters according to Ziegler-Nichols step

Type	Controller parameters		
	K_p	Ki	K_d
P	9.73	0	0
PI	8.76	0.08	0
PID	11.68	0.05	0.01

Figure 10 shows the comparison of step response of output flow between P, PI and PID controller graphically. In this figure, the response for the output rate of the P controller is in orange color, the response for the PI output rate is in red color and the response for the output rate of the PID controller is in blue color. Table 4 summarize the performance of each controller.

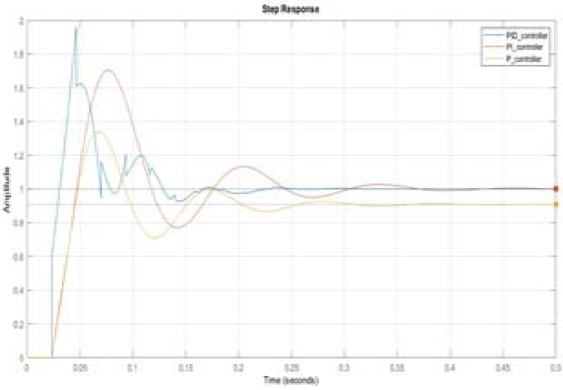


Figure 9: Step response of P, PI and PID controller

Table 4: Comparative performance between P, PI and PID controller

Controller	Maximum Overshoot	*Rise Time*	*Settling Time*	Steady state
P	*48%*	*0.018*	*0.28*	*0.907*
PI	*70 %*	*0.02*	*0.35*	*1*
PID	*96 %*	*0.006*	*0.21*	*1*

3.3 LQR controller:

In MATLAB K_{lqr} can be calculated using:

$$[K_{lqr}] = lqr(A, B, Q, R) \quad (12)$$

The simulation has been done with respect to the flowing consideration:

$$R = 1 \quad , Q = \lambda I \quad (13)$$

Where, $\lambda = 1$

Table 5 shows summarize the performance of LQR controller.

Table 5. LQR controller performance characteristics

Controller	*Rise Time*	Settling time	Steady state	Maximum Overshoot
LQR	49%	0.87	0.97	0%

4. RESULTS AND DISCUSSION

Figure 10 shows the comparison of step response of output rate between PI, PID and LQR controller graphically.

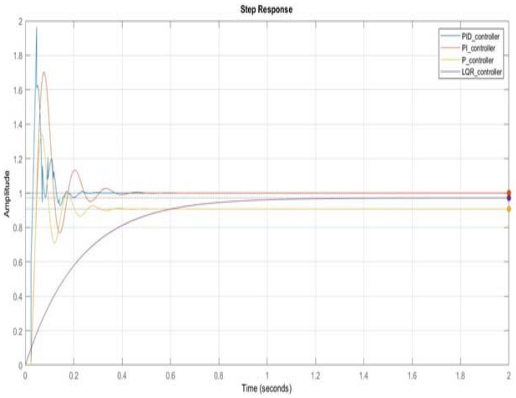


Figure 10. Step response of PI, PID and LQR controller

According to Table 6, we can clearly see that PID controller has the fastest rising time (0.0023 day) than P PI and LQR controllers. P controller has the fastest settling time of 0.0192 day. LQR has also the best value of settling time of 0.1738 day. However, for the percentage overshoot range, LQR controller has the best percent Overshoot (0 %) while P has the big percent Overshoot (48 %).

In addition, PI ad PID has the best steady state, of (1) compared to P controller (0.907) and LQR controller (0.971).Generally, all controllers are proved that

In conclusion, PID controller gives better performance in comparison to P, PI and LQR controller. Table 6 shows the summary of the performance characteristics of each controllers.

Table 6. Summary of the performance characteristics of P, PI, PID AND LQR controller

Controller	Maximum Overshoot	*Rise Time*	*Settling Time*	Steady state
P	*48%*	*0.018*	*0.28*	*0.907*
PI	*70 %*	*0.02*	*0.35*	*1*
PID	*96 %*	*0.006*	*0.21*	*1*
LQR	*0%*	*0.49*	*0.87*	*0.971*

5. CONCLUSION:

In this paper, an approach and a systematic design methodology to obtain a production and inventory control based on linearized transfer function and PID and LQR controller scheme as presented. The advantage of this approach is to generate a planning system suited to the production system being studied based on its actual data. A powerful of this methodology is to take into consideration the real behavior of the production system. The methodology contain 17 steps .The first step is data collection transfer function estimation and validation and control design: After extracting the input raw material flow and output flow data from ERP software of the company, the system identification toolbox in MATLAB is used to estimate and select the best model of assembly line behavior in the second and the third steps. Tow controllers are successfully designed in the fourth step: LQR and PID controllers. Based on the results and the analysis, a conclusion has been made that both of the control method, modern controller (LQR) and conventional controller (PID) are capable of planning and control of the flow of an assembly line. The responses of each controller are plotted in one window, figure 10, and are summarized in Table 6. Simulation results show that PID controller has better performance compared to LQR controller in controlling the assembly line.

In this work only SISO linearized production and system have been taken into consideration. There are many possibilities of future works using this approach. This work can be extended by considering MIMO model (Multiple input and Multiple Output) Multiple raw material input flow and multiple input product flow .This work would also extend to modeling simple and complex supply chain .This paper traits the linearized model that will be extended for the nonlinear control system. Other controllers will be used in the future such PIDPSO and PIDACO.

REFERENCES

[1] Ptak, Carol, and Chad Smith. 2011. Orlicky's Material Requirement Planning. 3rd ed. New York: McGraw Hill Professional.

[2] Ptak, Carol A., and Chad Smith. (2016). *Demand Driven Material Requirements Planning (DDMRP).* Norwalk, CT: Industrial Press.

[3] Orlicky, Joseph. (1975). Material *Requirements Planning: The New Way of Life in Production and Inventory Management.* New York: McGraw-Hill.

[4] Benton, W. C., and Hojung Shin. (1998). "*Manufacturing Planning and Control: The Evolution of MRP and JIT Integration."* European Journal of Operational Research 110 (3): 411–440. doi:10.1016/S0377-2217(98)00080-0.

[5] Goldratt, E. M., and J. Cox. (1993). *Le But: L'excellence En Production. 2nd ed. Paris: AFNOR Gestion.*

[6] *Goldratt, E. M., and R. Fox. 1986.* The Race. New York, NY: North River Press.

[7] S. Harwood. (*2003) ERP: The Implementation Cycle, Oxford, Butterworth Heinemann.*

[8] F.R. Jacobs, D.C. (2000). *Whybark, Why ERP? A Primer on SAP Implementation, McGrawHill, Boston.*

[9] Z. Zhang, M.K.O. Lee, P. Huang, L. Zhang, X. Huang. (2005) *A framework of ERP systems implementation success in China: an empirical study,* International Journal of Production Economics 98 (1) (2005) 56–80.

[10] Murilo Riyuzo Vendrame Takao, Jason Woldt, Iris *Bento da Silva.* (2017, October). *Six Sigma methodology advantages for small- and medium-sized enterprises: A case study in the plumbing industry in the United States.*First Published October 23, 2017 Research Article https://doi.org/10.1177/1687814017733248.

[11] E.O.Olumide, F.Sgarbossa, J.O.Strandhagen. (2020, May). *Smart Production Planning and Control Concept, Use-Cases and Sustainability*. "Sustainability, MDPI, Open Access Journal, vol. 12(9), pages 1-29, May".

[12] Wang Cheng, Liu Xiao-Bing. (2013, May). Integrated production planning and control: *A multi-objective optimization model. Journal of Industrial Engineering and Management.*Journal of Industrial Engineering and Management.JIEM, 2013 – 6(4): 815-830 – Online ISSN: 2013-0953 – Print ISSN: 2013-8423 http://dx.doi.org/10.3926/jiem.771.

[13] Grabot B., Blanc J.-C. and Binda C.(1996) *"A decision support system for production activity control Decision Support Systems"*, Vol. 16, N° 2, pp. 87–101, 1996.

[14] Porter, B., Zadeh, N. N. (1997). *Evolutionary design of fuzzy-logic controllers for manufacturing systems,* Annals of the CIRP, 46/1:425-428.

[15] Tamani K., Boukezzoula R. and Habchi G. (2006, October). *"Supervised Fuzzy Control in the Simulation of Manufacturing Systems"*, In Proceedings of the 20th annual European Simulation and Modelling Conference (ESM 2006), Toulouse, France, pp. 200–204, October 2006.

[16] Sheldon X.C. Lou. (1987, December) "Optimal control rules of for scheduling Job Shops", Massachusetts Institute of Technology December 25, 1987.

[17] Kimemia, J. G., Gershwin, S. B. (1983). *"An algorithm for the computer control of production in flexible manufacturing systems,* IIE Transactions", 15/4:353-362.

[18] Gershwin S. B. (1994). "*Manufacturing systems engineering, Prentice Hall, Englewood Cliffs*, NJ".

[19] Santiago Tosetti, Daniel Patino, Flavio Capraro, Adrian Gambier. (2008). *Control of a production-inventory system using a PID controller and demand prediction*, Proceedings of the 17th World Congress The International Federation of Automatic Control Seoul, Korea, July 6-11, 2008.

[20] D. Rivera, H. Lee, M. Braun and H. Mittelmann. (2003, August). *Plant-friendly system identification: a challenge for the process industries*, in Proc. 13th IFAC Symposium System Identification (SYSID 2003) (Rotterdam, Netherlands, 27–29 August 2003), pp. 917–922.

[21] C.C. Fang, K.J. Astrom, W.K. Ho. (1991). *Refinements of the Ziegler-Nichols tuning formula,*" IEEE proceedings-d, vol. 138, no. 2, March 1991.

[22] Jinghu Xing, workers Chen, Ming Jiang. (2007).*Linear the study of inverted pendulum optimal control system based on LQR.* Industrial Instrumentation and Automation.2007.6. Jian Pan, Jun Wang. (2008). *The study of two kinds control strategy based on inverted pendulum*. Modern electronic technology.2008.1.

[23] *L.* Ljung, R.Singh, Q.Zhang, P.Lindskog, A.Iouditski. (2009, July). *Developments in The MathWorks System Identification Toolbox.* 15th IFAC Symposium on System

Identification Saint-Malo, France, July 6-8, 2009.

[24] L.Ljung. (2007). *System Identification Toolbox for use with Matlab*. Version 7. The MathWorks, Inc, Natick, MA, 7th edition, 2007.

[25] L.Ljung, Q. Zhang, P. Lindskog, A. Juditsky, and R. Singh.(2006). *An integrated system identification toolbox for linear and non-linear models.* In Proc. 14th IFAC Symposium on System Identification, Newcastle, Australia, March 2006.

[26] JC. Ziegler, NB. Nichols, NY. Rochester (1942). *Optimum Settings for Automatic Controllers.*Trans ASME 65; 433-444.

[27] P.M. Meshram and Rohit G. Kanojiya, "Tuning of PID Controller using Ziegler-Nichols Method for speed control of DC Motor", March 2012.

[28] K. Astrom and T. Hagglund, "PID controller: Theory, Design and Tuning", 2 nd Ed, Library of congress cataloging-in-publication data, 1994.