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FUZZY SURPLUS BASED DISTRIBUTED CONTROL OF MANUFACTURING SYSTEMS

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Abstract:
This paper considers multiple-part-type production lines, and it views the overall production control system as a surplus-based system. A set of distributed single-level fuzzy controllers is used to reduce WIP and synchronize production system's operation. The overall control objective is to keep the WIP and cycle time as low as possible and, at the same time, satisfy demand, avoid overloading of the production system and synchronize the production system operation to eliminate machine starvation or blocking.

Key Words: Manufacturing Systems, Control, Fuzzy Surplus Method

1. INTRODUCTION

Production control policies include, among others, research on simulation studies of certain policies on specific systems; queuing theory based performance analysis, stability and optimal control, as well as fluid approximations of discrete systems. According to Gershwin [1] production control policies may be classified as token-based, time-based and surplus-based. Token-based systems, including Kanban, Production Authorization Card [2] and Extended Kanban Control Systems [3], involve token movement in the manufacturing system to trigger events. When an operation is performed or a demand arrives, a token is either created or taken from a specific location. Only when a token exists at the first location (and only if space for tokens exists at the second location) the operation takes place.

In surplus-based systems, decisions are made on the basis of how far cumulative production is ahead of or behind cumulative demand. Hedging-point, two-boundary and base-stock policies are based on surplus and backlog. Wein [4] found in an extensive series of experiments on simulations of semiconductor fabrication facilities that the most important factor in determining the performance of a factory was the process by which material is released into the system. Decisions made once the material is inside (sequencing, dispatching) are less important. Surplus-based systems may be viewed as a consequence of Wein's observation since the release policy is the most important factor in factory performance; the best policy is one that views all or many points as release points to the rest of the factory.

When considering simple manufacturing systems, analytical results produced thus far have demonstrated the superiority of surplus-based systems. More specifically, hedging point policies have been proven optimal in minimizing production cost in single-stage, single-part-type system scheduling [5, 6]. Generalizations to more than one-part-type or production stages have proven to be difficult [7, 8], but obtained solutions [9, 10] may be successfully applied in real manufacturing systems [11, 12].

In summary, it is a common belief among many researchers that for complex production systems the problem of scheduling, in order to minimize costs due to inventory and non-satisfaction of demand, cannot be solved analytically. Since neither analytical nor computational solutions are achievable, heuristic policies are suggested to control job flow within production systems [13 – 18].

This paper considers multiple-part-type production lines, and it views the overall production control system as a surplus-based system. A set of distributed single-level fuzzy controllers is used to reduce WIP and synchronize production system's operation. The overall control objective is to keep the WIP and cycle time as low as possible and, at the same time, satisfy demand, avoid overloading of the production system and synchronize the production system operation to eliminate machine starvation or blocking.

2. THE PRODUCTION CONTROL MODULES

According to the production floor modeling approach every manufacturing system may be decomposed into three basic modules: the line, assembly and disassembly module. The vast majority of production systems may be constructed by combining sets of these basic modules or subsystems. Therefore, manufacturing systems of random topology may be modeled and controlled based on the sets of the basic modules composing the overall system.

2.1 Fuzzy Control Representation

The subsystems may be seen as a fuzzy controller (Fig. 1). The input variables of each controller are:

- the buffers levels b_{ij} and b_{ik} of the upstream and downstream buffers,
- the state s_i of machine M_i,
- the production surplus x_i of M_i, which is the difference between actual production and demand.

The output variable of every controller is the processing rate r_i of each machine M_i.

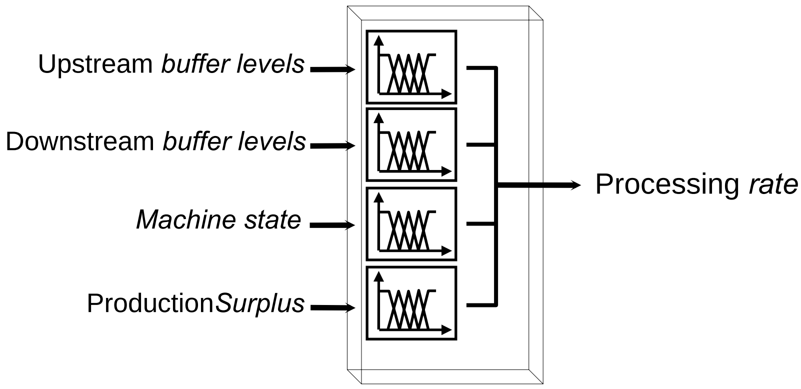

Figure 1: Inputs and output of the fuzzy controller.

The buffer levels, surplus and the processing rate of each machine take linguistic variation with certain membership functions. The machine state s_i is crisp and can be 1 (up) or 0 (down).

The control objective in all modules/subsystems and corresponding controllers is to meet the demand and the same time to keep WIP as low as possible. This is achieved as follows. At every time instant, the processing rate is regulated according to the following general rules:

- If the surplus level is satisfactory then try to prevent starving or blocking by increasing or decreasing the production rate accordingly.
- If the surplus level is not satisfactory meaning that is either too low or too high then produce at maximum or zero rates respectively.

A buffer tends to be empty when the upstream machine is either under repair or producing in a slower rate than the downstream machine. Similarly a buffer tends to fill when the downstream machine is either under repair or producing in a slower rate than the upstream machine. The controllers keep buffers neither full nor empty regulating the machine rates. When a buffer tends to be full the controller is increasing the rate of the downstream machine and decreasing the rate of the upstream machine. In the same way when a buffer tend to be empty the controller is increasing the rate of the upstream machine and decreasing the rate of the downstream machine. The information needed to synchronize the operation of the production network is transferred to each module controller by the change of buffer levels. Every event occurring in the production network is affecting the levels of buffers close to the area of the event. In that way the production system is operating in satisfactory rates while the WIP is kept in low levels.

The rule base of the line control module contains rules of the following form:

$$\textit{IF } b_{j,i} \textit{ is } LB^{(k)} \textit{ AND } b_{i,l} \textit{ is } LB^{(k)} \textit{ AND } ms_i \textit{ is } LMS_i^{(k)} \textit{ AND } x_i \textit{ is } LX^{(k)} \textit{ THEN } r_i \textit{ is } LR_i^{(k)} \qquad (1)$$

where,

- k is the rule number (k = 1, …, 18),
- i is the number of machine or workstation,
- LB is a linguistic value of the variable buffer level b with term set B = {Empty, Almost Empty, OK, Almost Full, Full},
- s_i denotes the state of machine i, which can be either 1 (operative) or 0 (stopped) and consequently:
  MS = {zero, one}.
- LX represents the value that surplus x takes, and it is chosen from the term set X = {Negative, OK, Positive}.
- The production rate r takes linguistic values LR from the term set R = {Zero, Low, Normal, High}.

The mathematical meaning of the k-th rule, for $LS_i^{(k)}$ = one, can be given as a fuzzy relation $FR^{(k)}$ on $B \times X \times R$, which in the membership function domain is

$$\begin{aligned}&\mu_{FR^{(k)}}(b_{j,i},\, b_{i,l},\, x_i,\, r_i) = f_{\rightarrow}[\mu_{LB^{(k)}}(b_{j,i}),\, \mu_{LB^{(k)}}(b_{i,l}),\\ &\mu_{LX^{(k)}}(x_i),\, \mu_{LR^{(k)}}(r_i)]\end{aligned} \qquad (2)$$

where, $f_{\rightarrow}$= denotes the implication operator, which is the min operator for rules of the Mamdani type [19]. Obviously, whenever $LS_i^{(k)}$ = zero, the production rate r takes the Zero value from the R term set.

Let us now assume that the machine is not stopped, and the actual buffer levels of the upstream and downstream buffers can be represented as $b_{j,i}^*$ and $b_{i,l}^*$ with membership functions $\mu_B^*(b_{j,i})$ and $\mu_B^*(b_{i,l})$, respectively. The production surplus at a given time instant is denoted as x_i^* with membership $\mu_X^*(x_i)$. The membership function of the conjunction of the three inputs, for AND = min, is

$$\mu_{AND}^*\left(b_{j,i}, b_{i,l}, x_i\right) = \mu_B^*\left(b_{j,i}\right) \wedge \mu_B^*\left(b_{i,l}\right) \wedge \mu_X^*\left(x_i\right) \qquad (3)$$

The production rate r_i^*, e.g. the control action at every time instant is given by

$$r_i^* = \frac{\sum r_i \cdot \mu_R^*(r_i)}{\sum \mu_R^*(r_i)} \qquad (4)$$

where, $\mu_R^*(r_i)$ is the membership function of the aggregated production rate, which is computed by applying the max-min composition on the outcome of (2) and (3). That is:

$$\mu^*_R(r_i) = \max_{b_{j,i},b_{i,l},x_i} \min[\mu^*_{AND}(b_{j,i}, b_{i,l}, x_i), \mu_{FR^{(k)}}(b_{j,i}, b_{i,l}, x_i, r_i)] \quad (5)$$

Similarly, the generic rule of the assembly and disassembly control modules may be written as follows:

$$IF\ b_{j,i}\ is\ LB^{(k)}\ AND \ldots AND\ b_{i,l}\ is\ LB^{(k)}\ AND\ ms_i\ is\ LMS_i^{(k)}\ AND\ x_i\ is\ LX^{(k)}\ THEN\ r_i\ is\ LR_i^{(k)} \quad (6)$$

The formulation presented in this section can be expanded to multiple-part-type production lines or networks without major modifications. The structure of fuzzy controllers remains the same since a multiple-part-type system can be decomposed into single part type systems.

3. SIMULATION RESULTS AND COMPARISONS

In this section, we test the proposed control approach and compare its performance to other well known control approaches. We assume that the flow of parts within the system is continuous. In the continuous-flow simulation the discrete production is approximated by the production of a liquid product [20]. The assumptions we made for all simulations, are the same as in the previous chapter.

3.1 Test Case: Single-part-type transfer lines

The developed fuzzy controller is tested for the case of the single product transfer line presented in Fig. 2. The production line consists of five machines and four interstation buffers. The first buffer, denoted B_I, is an infinite source while the last buffer B_F has infinite storage capacity. The system is balanced.

All machines have the same processing time, $T_i = 0.5$ ($i = 1, \ldots, 5$), and the same failure and repair probabilities, $p_i = 0.1$ and $rr_i = 0.5$, respectively.

The transfer line of Fig. 2 is identical to one presented by Bai and Gershwin (test case 5 in [21]), and it was selected to facilitate comparisons. The performance of our controller is compared to the classical produce-at-capacity approach, according to which the machines produce in their maximum rate when they are operational (up, not blocked, not starved). This is similar to what is known as bang-bang control.

The approach was presented by Bai and Gershwin in [13], [15] and elsewhere. Their method is based on the determination of a desirable production surplus value, the hedging point.

When the machine is up, the control law is summarized in the following:

- If the actual surplus is less than the hedging point, then the machine should produce at its maximum rate.
- If surplus is equal to the hedging point, the production rate should be equal to demand.
- If surplus is greater than the hedging point, stop producing.

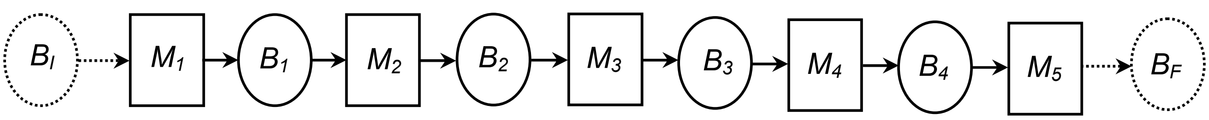

Figure 2: The transfer line of test case 1.

The proposed single-part-type transfer line controller contains 18 fuzzy IF-THEN rules. A part of the actual rule base is presented in Table I. Main control objective is to maximize the utilization of machines by avoiding starvation and/or blocking. Simultaneously, production surplus should be close to zero in order to satisfy demand.

The control methods are examined for five different demand values. For each demand, various simulation runs were performed with different random number seeds. All results are averaged over the number of simulation experiments. Buffer capacities are given and presented in Table II. Figure 3 represents graphically the WIP inventory of each method. It can be seen that the proposed approach keeps the in-process inventories significantly lower than the other two methods for all demands. Numerical results are presented in Table III.

Table I: Part of controller's rule base.

Rule	Inputs				Output
	LB_i	LB_{i+1}	MS_i	X_i	R_i
1	OK	Almost full	1	OK	Low
2	Any	Full	1	Any	Zero
3	Not empty	Not full	1	Negative	High
4	OK	OK	1	OK	Normal
5	Full	Almost empty	1	OK	High
6	Any	Any	0	Any	Zero
7	Not empty	Empty	1	Any	High

Table II: Buffer sizes and demand levels for test case 1.

Demand *d*	Buffer Capacity			
	BC_1	BC_2	BC_3	BC_4
1.6	6	6	8	5
1.4	3	3	10	1
1.2	1	4	5	1
1.0	1	1	1	1
0.6	1	1	1	1

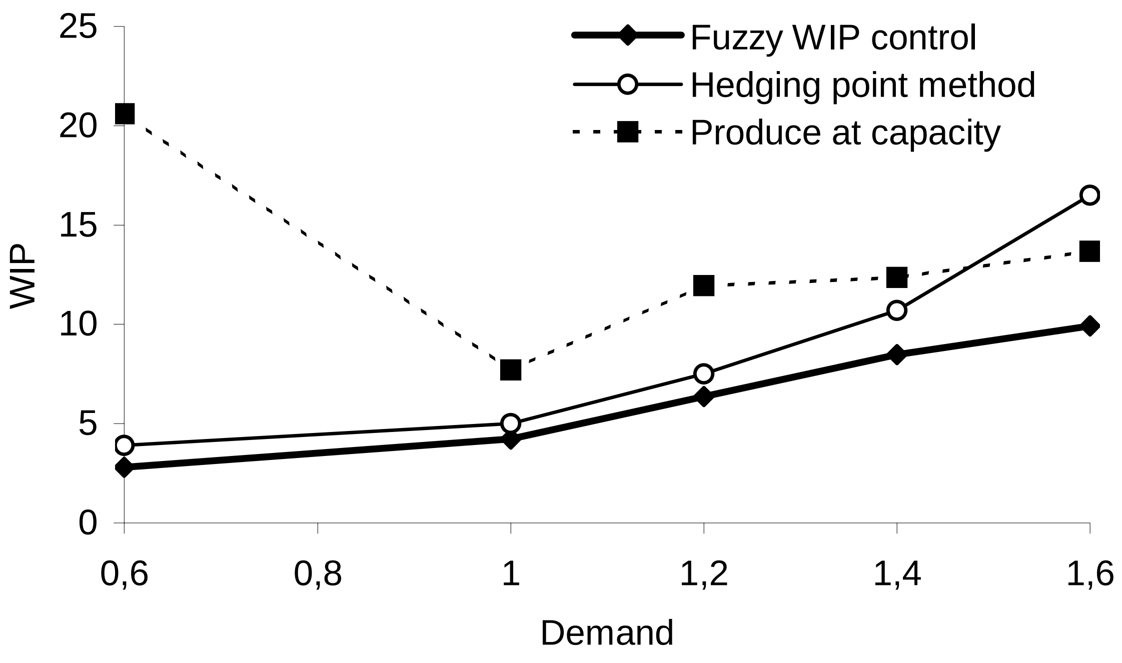

Figure 3: In-process inventory for test case 1.

Table III: Average buffer level and WIP inventory for test case 1.

Demand	Average Buffer levels for Fuzzy WIP Control				Work-in-process inventory		
	B_1	B_2	B_3	B_4	Fuzzy WIP control	Hedging point method	Produce at capacity
1.6	0.97	1.42	2.77	0.77	9.93	16.5	13.67
1.4	0.74	0.67	3.22	0.35	8.48	10.7	12.36
1.2	0.78	1.36	1.02	0.21	6.37	7.5	11.96
1.0	0.83	0.43	0.26	0.21	4.23	5	7.71
0.6	0.52	0.33	0.19	0.26	2.8	3.9	20.6

3.2 Test Case 2: Multiple-part-type transfer lines

In this section the performance of the transfer line controller is demonstrated, for the case of multiple-part-type production lines. The production system under consideration consists of three machines and produces three product types. Buffers with finite storage capacity are located between machines. The first buffer for each product is assumed to be an infinite source while the last is an infinite sink. All machines are subject to random failures and repairs with known rates.

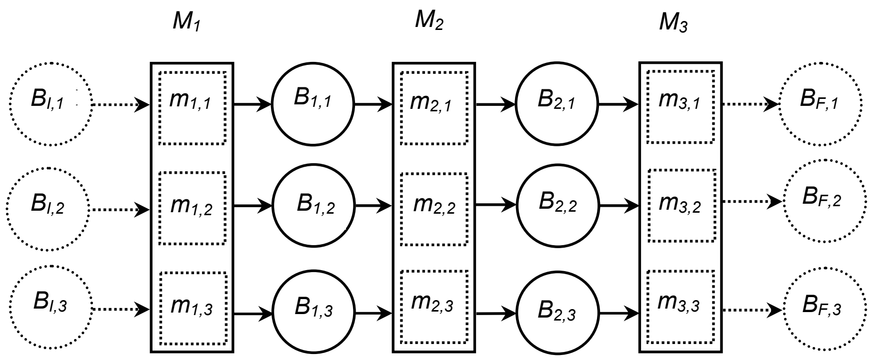

Figure 4: Test case 2: 3-machine, 3-part-type production line.

System data and structure are identical to an example presented in [14] by Bai and Gershwin. Each machine is "virtually" divided in as many sub-machines (or *partial machines* [14]) as the number of part types to be processed. Consequently, the 3-part-type system under study, illustrated in Fig. 4, can be approximated by three single-type systems similar to one analyzed in the previous section. Partial machines are presented in Fig. 4 with dotted line squares. Each machine i performs operations on parts of j type and it is divided into m_{ij} partial machines (here $i = j = 1,\ldots,3$). Each m_{ij} does one operation on the type j part, which then waits in the b_{ij} buffer for an operation at the $m_{i+1,j}$ partial machine. The demand for parts of type j is d_j. The failure and repair rate of machine i is p_i and rr_i, respectively. The processing times τ_{ij} are chosen as follows (Table IV) [14]:

Table IV: Machines Processing Times.

Part type	Machine		
	1	2	3
1	0.5	0.3	0.4
2	0.3	0.2	0.3
3	0.4	0.4	0.5

Failure rates are p_1 = 0.1, p_2 = 0.01 and p_3 = 0.2, and repair rates are rr_1 = 0.5, rr_2 = 0.8, rr_3= 0.6. Buffer sizes are all equal to 1 and demand is assumed to be constant over time for each part type (d_1 = 0.8, d_2 = 0.6, d_3 = 0.3). The WIP was calculated for each product after multiple simulation runs using different seeds. These results are shown below:

$$\mathrm{WIP}_1 = 1.369 \qquad \mathrm{WIP}_2 = 0.988 \qquad \mathrm{WIP}_3 = 0.667$$

The fuzzy WIP controller satisfied the demand (which is selected low anyway) and kept the total WIP 20 % less than in [30].

3.3 Remarks

From the simulation results may be concluded that the fuzzy WIP controller keeps lower in-process inventories compared to the other approaches examined, that is, produce-at-capacity and hedging point [14], [15], [22] methods. The main advantage of the fuzzy WIP controller is that approximates the way human operators adjust the processing rate of machines so as to minimize idle periods due to starving or blocking. Two possible drawbacks can be identified. The first concerns the ease of the WIP controller implementation. Real-time regulation of processing rate requires on-line monitoring of buffer levels and production surplus. This might be unrealistic in practice. The second remark is associated with the decision space complexity of the fuzzy WIP controller. The produce-at-capacity policy follows just one control rule: IF machine is not down THEN produce at the maximum rate. Despite the fact that the bang-bang behaviour of this policy is not appropriate for regulation problems, it has gained wide acceptance in production control practice because of its simplicity (and high throughput). Similarly, the hedging point method uses only three control rules to adjust machine's processing rate, in contrast to the rule base of the fuzzy WIP controller for transfer lines (either single or multiple part types) which contains 18 rules. It should be noted that although it might be a problem in systems of larger size, we haven't observed any significant delay in computations that can be attributed to the number of rules.

4. CONCLUSIONS

A distributed fuzzy controller has been presented, which keeps production close to demand and WIP inventories in low levels by regulating the processing rate of each machine. The proposed control system consists of three independent modules and can be applied to production networks of general topology. The structural advantage of the approach presented here is that allows for an operator-like knowledge representation and reasoning. Numerous simulation experiments verified controller's good performance. A continuous-flow simulator is used to compare the proposed WIP controller with produce-at-capacity and hedging point methods. For the test cases examined, it turned out that the fuzzy policy provides lower WIP, higher system utilization, and smaller product cycle time.

An interesting extension, to be considered in the future, would consist of examining the performance of WIP controller when applied to reentrant systems, in which parts may visit some machines more than once. More complex patterns of demand should be considered.

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