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Dynamics of WIP Regulation in Large Production Networks of Autonomous Work Systems

Neil A. Duffie and Leyuan Shi

***Abstract*—In this paper, dynamic behavior is compared for two methods of local work in progress (WIP) regulation in autonomous work systems in production networks. In one method, work systems do not share information regarding the expected physical flow of orders between them; in the other, order-flow information is shared to compensate for the variable dynamic effects of physical order-flow coupling. In both methods, the work systems adjust production rate with the objective of maintaining a desired amount of local WIP. A linear discrete-time dynamic model of the flow of orders between work systems is used, which promotes identification of fundamental properties such as characteristic times and damping. The results demonstrate the need for order-flow information sharing in establishing desired network dynamic behavior. Examples are used to illustrate behavior in the general case of omnidirectional order flows and the special case of unidirectional order flows.**

***Note to Practitioners*—In the type of production network analyzed in this paper, each work system autonomously adjusts its production rate with the objective of maintaining a desired amount of local work waiting to be processed. It is known that production networks can exhibit unfavorable dynamic behavior; for example, oscillation of inventory in supply chains as suppliers respond individually to variations in orders, leading to recommendations that supply chains should be globally rather than locally controlled. However, decentralized planning and control methods are an increasingly important alternative. Dynamic models are used in this paper to demonstrate the need for and benefits of order-flow information sharing between the work systems to compensate for variations in the structure of physical order flows in such networks. The goals are to avoid slow or oscillatory response to disturbances and to establish and maintain desired network dynamic properties, particularly when the structure of order flows in the network is omni-directional.**

***Index Terms*—Autonomy, distributed control, dynamic modeling, production systems.**

I. INTRODUCTION

Production networks can exhibit unfavorable dynamic behavior. An example is oscillation of inventory in supply chains as individual organizations respond individually to variations in orders, leading to recommendations that supply chains should be globally rather than locally controlled and that information sharing should be extensive [1], [2]. Unfortunately, it is difficult to make all of the information necessary for robust control available to a centralized planning and control entity, especially when there are a large number of work systems in a production network. It is now recognized that decentralized coordination can be provided by logistic processes implemented by autonomous entities that can be the logistic objects themselves [3]. Decentralized planning

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and control methods, that are heterarchical rather than hierarchical in nature, are an increasingly important alternative in which synchronization of decisions is based on cooperation among entities that use limited global information and communicate as peers [4], [5]. However, achieving effective cooperation and choosing the appropriate level of autonomy remain significant challenges in design of autonomous logistic systems [6], [7].

Decision making in production networks has been analyzed using linear and nonlinear dynamical models developed for control of variables such as inventory levels and work in progress (WIP). Pipeline flow concepts have been used to represent lead times and production delays [8]–[12]. Application of control theory to the production inventory problem has been reviewed [13], and control-theoretic approaches have been used to model supply chain management, including the use of differential equations to study the stability of adjustments in inventories and production rates [14]–[17]. A flow control approach has been applied to model decision making in high volume manufacturing-oriented scheduling where rates rather than events are controlled [18]. Concepts of temperature and diffusion have been used in kinetic and fluid models for supply chains, and discrete event simulations have been used to generate parameterizations for partial differential equation models [19], [20]. State-space models have been used for switching between a library of optimal controllers to adjust WIP in serial production systems in the presence of machine failures [21], and switching of control policies in response to market strategies has been investigated [22].

Due to the complexity of interactions between decision-making entities in production networks, modeling their behavior has remained a challenge [23]–[26]. This is particularly so when control is decentralized and decision-making is heterarchical and cooperative rather than hierarchical. Such systems require coupling structures that create the information-based interactions necessary to ensure that local actions are globally effective [27]. These often are closed-loop structures, and the control laws and heuristic rules chosen must create well-behaved network dynamics including desired responsiveness, absence of oscillatory behavior, and robustness in the presence of uncertainties.

There is a need to ensure that disturbances in one portion of a production network do not propagate, and to ensure that the dynamic behavior of the network remains as designed and does not change unpredictably or unfavorably with time. In this paper, dynamic properties are compared for two methods of local WIP-regulation in large networks of autonomous work systems. The two methods incorporate different levels of information sharing between work systems in a network:

- *No information sharing between work systems*: The work systems do not share information regarding the expected physical flow of orders between them. A production rate plan is required for each work system.
- *Sharing of order-flow information between work systems*: The work systems share order-flow information to anticipate and compensate for the expected dynamic effects of order flows between work systems. No production rate plan is required.

In both methods, the work systems adjust production rate with the objective of maintaining a desired local level of WIP. WIP is an important and readily measured logistic variable and the desired local level of WIP can be chosen, for example, to trade off lead times and work system utilization [28], [29]. The desired WIP can be locally specified or planned at a higher level by entities outside the network; it need not be constant.

A dynamic model is developed for each of these WIP-regulation methods, in which it is assumed that local production rate is periodically adjusted, for example daily, weekly or per shift. A linear discrete-time approach is used for modeling the dynamic flow of orders into, out of, and between work systems. Orders are used as the dependent variable rather than hours of work content, with the assumption that orders are conserved as they move from work system to work system [30]. The units of work system production rate and order input rate are orders per shop calendar day (orders/scd).

Buffer size limitations and setup and transportation times are not modeled. Furthermore, it is assumed that production rates are not limited, and adjustments in production rate can be of any magnitude (labor work rules, number of shifts, number of machines, etc., are not modeled.) The time between production rate adjustments is assumed to be constant, and adjustments are assumed to take place simultaneously in all work systems. The possibility of delay in implementing production rate adjustments is modeled, and this delay is assumed to be constant, the same for all work systems, and an integer multiple of the period between adjustments. Production rates, order input rates, work disturbances, etc., are assumed to be constant between production rate adjustments. Order processing times are ignored, and the sequence of order processing is not considered.

While these assumptions significantly reduce time-domain modeling fidelity, they permit linear control theory to be used to gain substantial and valuable insight into the fundamental dynamic properties of a production network. Furthermore, they facilitate demonstration of the benefits of information sharing in establishing and maintaining desired fundamental dynamic properties in a network. In the following sections, this is done first using a single work system and then using examples with five work systems. The significant potential of omnidirectional order flows to change the dynamic properties of a network is investigated, as well as the special case of unidirectional order flows.

II. DYNAMIC MODELS FOR WIP REGULATION IN AUTONOMOUS WORK SYSTEMS

Assume that there are N work systems in a production network. Inputs to the network are assumed to be constant during time $kT \leq t < (k+1)T$, where $k = 0, 1, 2, \ldots$ and T is the time period between production rate adjustments in each work system. The total orders input to the work systems up to time $(k+1)T$ are

$$\boldsymbol{w}_i((k+1)T) = \boldsymbol{w}_i(kT) + T(\boldsymbol{i}(kT) + \boldsymbol{P}(kT)^T \boldsymbol{c}_a(kT)). \tag{1}$$

Vector $\boldsymbol{i}(kT)$ represents the rates at which orders are input to the N work systems from sources external to the production network, and vector $\boldsymbol{c}_a(kT)$ represents the rates at which orders are output from the N work systems. $\boldsymbol{P}(kT)$ is a matrix in which each element $p(kT)_{\mathrm{nj}}$ represents the fraction of the orders flowing out of work system n that flow into work system j during time $kT \leq t < (k+1)T$ [18]. $\boldsymbol{P}(kT)$ is assumed to be constant during this period.

The total orders that have been output by the work systems up to time $(k+1)T$ are

$$\boldsymbol{w}_o((k+1)T) = \boldsymbol{w}_o(kT) + T\boldsymbol{c}_a(kT) \tag{2}$$

while the rates at which orders are output from the network during time $kT \leq t < (k+1)T$ are

$$\boldsymbol{o}(kT) = \boldsymbol{P}_o(kT)\boldsymbol{c}_a(kT) \tag{3}$$

where $\boldsymbol{P_o}(kT)$ is a diagonal matrix in which nonzero element $p_o(kT)_{nn}$ represents the fraction of orders flowing out of work system n that flow out of the network during time $kT \leq t < (k+1)T$, and

$$p_{o_{nn}}(kT) + \sum_{j=1}^{N} p_{nj}(kT) = 1. \tag{4}$$

$\boldsymbol{P}(kT)$ and $\boldsymbol{P_o}(kT)$ represent the structure of network order flow.

The WIP levels in the work systems are

$$\boldsymbol{wip}_a(kT) = \boldsymbol{w}_i(kT) - \boldsymbol{w}_o(kT) + \boldsymbol{w}_d(kT) \tag{5}$$

where $\boldsymbol{w}_d(kT)$ represents disturbance inputs such as rush orders that affect the individual work systems in the network.

It is desired to maintain WIP in the vicinity of plan inputs $\boldsymbol{wip}_p(kT)$. The WIP errors

$$\boldsymbol{wip}_e(kT) = \boldsymbol{wip}_a(kT) - \boldsymbol{wip}_p(kT) \tag{6}$$

can be reduced by using a straightforward control law in making production rate adjustments

$$\Delta\boldsymbol{c}(kT) = k_c\boldsymbol{wip}_e(kT). \tag{7}$$

A lower value of control parameter k_c tends to produce a more slow-acting dynamic system and, within limits, a higher value of k_c tends to produce a more fast-acting system [27]. While each work system could have a different value of k_c, here it is assumed to be the same throughout the network.

The following subsections describe how full production rate $\boldsymbol{c}_f(kT)$ is adjusted in the two methods of WIP regulation that were studied. In both methods, application of these production rate adjustments is assumed to be delayed by d time periods, representing the realities of labor contracts and other logistic issues that prevent instantaneous adjustment of production rate. Furthermore, the actual production rate can be less than the full production rate due to disturbance inputs $\boldsymbol{c}_d(kT)$ such as operator illness, equipment failure, and material shortages

$$\boldsymbol{c}_a(kT) = \boldsymbol{c}_f(kT) - \boldsymbol{c}_d(kT). \tag{8}$$

A. *No Order-Flow Information Sharing*

Consider a network in which no information is shared between work systems and in which work system production rate plans $\boldsymbol{c}_p(kT)$ are supplied at least time dT in advance by a source external to the network. The work systems independently rather than collaboratively adjust their production rates and therefore are coupled by physical order flows, but not by order-flow information sharing. The production rate plans may be constant or time varying, and the work systems adjust their local full production rate with respect to the production rate plan

$$\boldsymbol{c}_f((k+d)T) = \boldsymbol{c}_p((k+d)T) + \Delta\boldsymbol{c}(kT). \tag{9}$$

Work system n then will use $c_f((k+d)T)_n$ time dT later to set its production rate; however, as indicated by (8), actual production rate can differ from full production rates because of disturbances.

From (1) through (9), it can be shown that the fundamental dynamic properties of the network (possibility of oscillation when disturbed, time to respond to changes in plans, time to recover from disturbances, etc.) with constant order-flow structure $\boldsymbol{P}$ are characterized by the roots of

$$\det((1 - z^{-1})\boldsymbol{I} + k_cT(\boldsymbol{I} - \boldsymbol{P}^T)z^{-(d+1)}) = 0. \tag{10}$$

The order-flow structure $\boldsymbol{P}$ and the choice of k_c, T and d will affect these dynamic properties. Also, the dynamic properties of the network can change with time if the order-flow structure is not constant.

This method can produce significant deviation of WIP from plan if the work system production rates required to satisfy order flows entering from outside network and from other work systems deviate significantly from planned production rates. The steady-state deviation of WIP from plan with constant inputs $\boldsymbol{i}(kT) = \boldsymbol{i}_{ss}, \boldsymbol{c_p}(kT) = \boldsymbol{c}_{p_{ss}}, \boldsymbol{c}_d(kT) = \boldsymbol{c}_{d_{ss}}$ then is

$$\mathbf{wip}_{e_{ss}} = \frac{1}{k_c}((\boldsymbol{I} - \boldsymbol{P}^T)^{-1}\boldsymbol{i}_{ss} - \boldsymbol{c}_{p_{ss}} + \boldsymbol{c}_{d_{ss}}). \tag{11}$$

B. *Sharing of Order-Flow Information*

It is clear that the fundamental dynamic properties of the network are a function of order-flow structure. With the objective of establishing and maintaining constant and desirable fundamental dynamic properties, consider a network in which each work system shares order-flow information with all other work systems in the network, allowing individual work systems to locally compensate for varying physical order-flow coupling. To use this information, the production rate adjustments described by (9) can be modified

$$\boldsymbol{c}_m((k+d)T) = \boldsymbol{i}'((k+d)T) + \Delta\boldsymbol{c}(kT) \tag{12}$$

where $\boldsymbol{i}'((k+d)T)$ is the vector of expected inputs from sources external to the network, which is assumed to be known at least time dT in advance. Each work system n shares its result $c_m((k+d)T)_n$, and its components of $\boldsymbol{P}'((k+d)T)$ when the order-flow structure is variable, with all other work systems in the network. Then, all work systems adjust their full production rates using

$$\boldsymbol{c}_f((k+d)T) = (\boldsymbol{I} - \boldsymbol{P}'^T((k+d)T))^{-1}\boldsymbol{c}_m((k+d)T) \tag{13}$$

where expected order-flow structure $\boldsymbol{P}'((k+d)T)$ is assumed to be known at least time dT in advance. Again, work system n will use

$c_f((k+d)T)_n$ time dT later to set its production rate, resulting in an actual production rate as given by (8).

With this method of WIP regulation, the fundamental dynamic properties of the network with constant order-flow structures $\boldsymbol{P}$ and $\boldsymbol{P}'$ are characterized by the roots of

$$\det\left((1-z^{-1})\boldsymbol{I}+k_cT(\boldsymbol{I}-\boldsymbol{P}^T)\times\left(\boldsymbol{I}-\boldsymbol{P}'^T\right)^{-1}z^{-(d+1)}\right)=0. \qquad (14)$$

If $\boldsymbol{P}\approx\boldsymbol{P}'$, then the fundamental dynamic properties of the network are no longer a function of order flow structure and can be established by choosing k_c, given T and d.

For this method, the steady-state deviation of WIP from plan is as follows when inputs are constant:

$$\boldsymbol{wip}_{e_{ss}}=\frac{1}{k_c}\left((\boldsymbol{I}-\boldsymbol{P}'^T)(\boldsymbol{I}-\boldsymbol{P}^T)^{-1}\boldsymbol{i}_{ss}-\boldsymbol{i}'_{ss}+(\boldsymbol{I}-\boldsymbol{P}'^T)\boldsymbol{c}_{d_{ss}}\right). \qquad (15)$$

If $\boldsymbol{P}\approx\boldsymbol{P}'$ (the actual order-flow structure is approximately equal to the expected structure), $\boldsymbol{i}\approx\boldsymbol{i}'$, (the actual order-flow input from sources external to the system is approximately equal to the expected input) and $\boldsymbol{c}_{d_{ss}}\approx\boldsymbol{0}$, then the deviation of WIP from plan can be expected to be small with this method.

III. DETERMINATION OF EXPECTED ORDER-FLOW STRUCTURE

The work content and routing of orders, as well as adjustments in production rate, will affect order completion times in reality and hence will affect the structure of flow of orders between work systems. When this structure is variable, then $\boldsymbol{P}'((k+d)T)$ may need to be collectively assembled by the work systems at the beginning of each period T [27].

IV. SPECIAL CASE OF UNIDIRECTIONAL ORDER-FLOW

In general, order flows can be omnidirectional because of rework, planned return of orders to work systems for subsequent processing, the presence of orders with different routings (for example, order type A with route through work systems $\langle 1,2,3,4\rangle$ and order type B with route $\langle 2,3,1,4\rangle$), etc. In the special case of a unidirectional order-flow structure, upstream work systems do not receive work from downstream work systems, and the work systems can be numbered such that $p_{nj}=0$ for $j\leq n$. The fundamental dynamic properties of each work system then are described by the roots of

$$1-z^{-1}+k_cTz^{-(d+1)}=0 \qquad (16)$$

which are not a function of order-flow structure. Furthermore, the fundamental dynamic properties of the production network are similar to those of work systems in series.

V. SINGLE WORK SYSTEM WITH REENTRY ORDER FLOW

Consider a single work system in which a fraction p_{11} of its output order flow reenters the work system. The single work system is assumed to possess an estimate p'_{11} of p_{11}. (p'_{11} represents the expected order-flow structure, while p_{11} the actual order-flow structure.) From (14), the characteristic equation for the single work system is

$$1-z^{-1}+k_cT\frac{(1-p_{11})}{(1-p'_{11})}z^{-(d+1)}=0. \qquad (17)$$

TABLE I
DYNAMIC PROPERTIES OF A SINGLE WORK SYSTEM FOR VARIOUS EXPECTED AND ACTUAL ORDER-FLOW STRUCTURES FOR $T=1$ SCD, $d=1, k_c=0.25$ SCD^{-1}

	Characteristic roots	Damping ratio	Characteristic times [scd]
$p'_{11}=p_{11}$	0.5 0.5	1.0	1.4 1.4
$p_{11}=0$ $p'_{11}=0.36$	0.5+j0.38 0.5-j0.38	0.6	2.1
$p_{11}=0.36$ $p'_{11}=0$	0.8 0.2	-	4.5 0.6

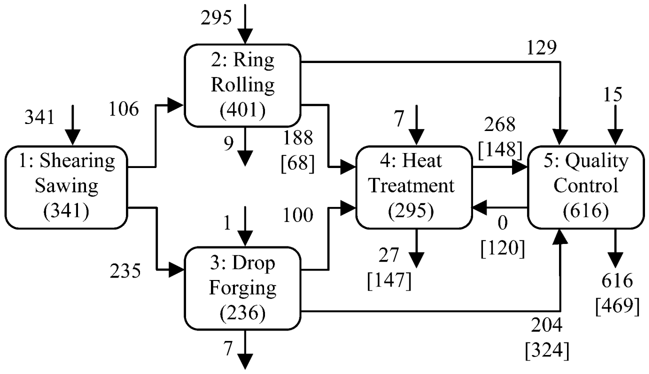

Fig. 1. Examples of unidirectional and omnidirectional order-flow structures [omnidirectional example where different].

Table I shows the discrete characteristic roots and equivalent damping ratios and characteristic times for several examples when $T=1$ scd, $d=1$ (delay dT is 1 scd), and $k_c=0.25$ scd^{-1}. A 0% reentry flow when 36% is expected results in oscillatory behavior in WIP and production rate. A 36% reentry order flow when 0% is expected triples the time required to respond to inputs such as rush orders. Furthermore, results with no order-flow information sharing are equivalent to results with $p'_{11}=0$. Clearly, if the expected order-flow structure differs from the actual structure, or order flows are omnidirectional without information sharing, then dynamic properties can be significantly affected.

VI. FIVE-WORK-SYSTEM NETWORK EXAMPLES

Consider the two examples in which 659 orders flow over a 185-day period in a five-work-system network as illustrated in Fig. 1. In the first example, order flow is unidirectional but in the second example, flow is omni-directional because one order type (120 orders in total) flows from shearing-sawing to quality control to heat treatment rather than from shearing-sawing to heat treatment to quality control. In both examples, the matrix $\boldsymbol{P}$ can be calculated from the data in Fig. 1 by assuming that the order-flow structure is constant.

Table II shows the discrete characteristic roots and equivalent damping ratios and characteristic times obtained for change in WIP

TABLE II
DYNAMIC PROPERTIES OF THE HEAT TREATMENT AND QUALITY CONTROL WORK SYSTEMS FOR $T = 1$ SCD, $d = 1, k_c = 0.25$ SCD^{-1}

		Work system	Characteristic roots	Damping ratios	Characteristic times [scd]
Without information sharing	Uni-directional	Heat treatment	0.5 0.5	1.0 1.0	1.4 1.4
		Quality control	0.5 0.5 0.5 0.5	1.0 1.0 1.0 1.0	1.4 1.4 1.4 1.4
	Omni-directional	Heat treatment Quality control	0.7796 0.2204 0.5000 ± 0.2796i	- - 0.7	4.0 0.7 1.8
With sharing	Both cases	Heat treatment	0.5 0.5	1.0 1.0	1.4 1.4
		Quality control	-	-	-

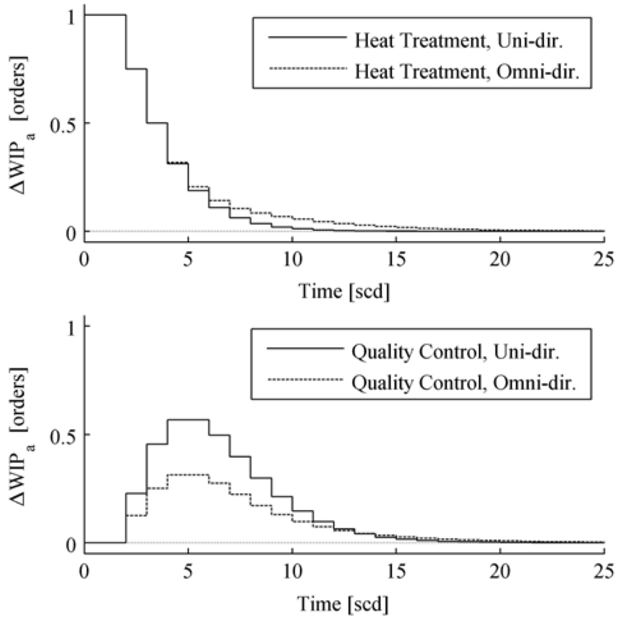

Fig. 2. Change in WIP after a one-order disturbance at the heat treatment work system without order-flow information sharing.

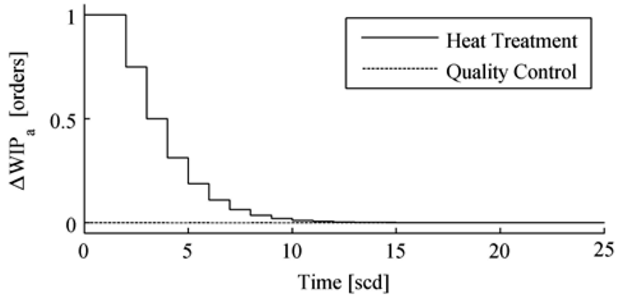

Fig. 3. Change in WIP after a one-order disturbance at the heat treatment work system with order-flow information sharing.

as a function of work disturbances at the heat treatment work system (such as a rush order), with and without order-flow information sharing, and with $T = 1$ scd, $d = 1$ (delay dT is 1 scd), and $k_c = 0.25$ scd^{-1}. Only heat treatment and quality control are affected by these work disturbances. Without order-flow information sharing, the two work systems are mutually coupled dynamic systems in the omnidirectional flow example, but are dynamic systems in series in the unidirectional example. Changes in WIP in response to a one-order work disturbance are shown in Fig. 2, where the longer characteristic time of the omnidirectional flow example is evident. With order-flow information sharing, the responses in Fig. 3 illustrate that order-flow structure no longer influences the fundamental system dynamics and WIP variation does not propagate to other work systems.

VII. CONCLUSION

Two methods have been described in this paper for local regulation of WIP in autonomous work systems in production networks. Reduced WIP variation can reduce lead-time variation and can simplify production planning and scheduling. In the first method, no order-flow information is shared between work systems, and it has been shown that an effective production rate plan is required if deviations in WIP from desired values are to be avoided. It may be a challenge for entities external to the network to generate such a plan because the work systems autonomously adjust their production rates, explicitly deviating from the plan. Furthermore, reliance on an externally supplied production rate plan reduces autonomy of the work systems and the network as a whole.

In the second method, order-flow information is shared between work systems, and order flows within the network do not need to be predicted by external planning entities. Only order flows into the network from external sources need to be predicted. This difference is important because while order flows within the network may be difficult for external planners to accurately predict, order flows into the network originate in external sources and therefore are likely to be more accurately known. For this method, it was shown that the deviations in WIP from desired values are theoretically zero in the absence of internal disturbances when the order-flow structure is known and expected input order flows from external sources are equal to the actual order flows. In both methods, only local information is shared between work systems, and knowledge is gathered and shared when it is needed; there is no requirement for archiving shared information in a centralized database, improving autonomy and robustness.

For the general case of omnidirectional order-flow structures, it was shown that the dynamic behavior of the network is a function of order-flow structure. Inaccurate or non-existent compensation for order-flow structure can result in dynamic behavior that deviates from that desired, potentially becoming oscillatory and potentially requiring longer time periods to react to disturbances. For the special case of unidirectional order-flow structures, the local dynamic behavior of the work systems is not affected by the order-flow structure, and the dynamic behavior of the network is characterized by series combinations of work-system dynamics. Order-flow information sharing still is beneficial in this case because it curtails propagation of disturbances to downstream work systems.

Dynamic behavior can be improved by decreasing the time period between production rate adjustments, and by decreasing the delay in making production rate adjustments. This delay represents the inability to make instantaneous adjustments, but related work rules and equipment limitations have not been addressed, nor have other logistic issues such as production rate limits, buffer size limits, setup times, transportation times, starvation of work systems with low WIP, and the work content of orders. Further research is required to quantify their effects on fundamental dynamic behavior.

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