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Maintaining constant WIP-regulation dynamics in production networks with autonomous work systems

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ABSTRACT

In this paper, a method is presented for information sharing in production networks with large numbers of autonomous work systems for the purpose of maintaining constant dynamic properties when the structure of physical order flows between the work systems is omni-directional and variable. It is shown that information sharing is necessary if undesirable behaviors such as oscillation or slow response are to be avoided. A method for designing the dynamic properties of such networks is presented along with a method for distributed computation and communication of information needed to locally compensate for the expected order flows from other work systems.

1. Introduction

The ability to establish and maintain desirable dynamic behavior is essential in production networks. This can be a particularly significant challenge when the individual work systems in a network have high levels of local autonomy, and cooperation and information sharing are used to ensure effective operation, rather than centralized control. Production networks are known to exhibit unfavorable dynamic behavior; for example, inventory levels can oscillate in supply chains as organizations respond individually to variations in orders [1]. Decentralized planning and control methods are an increasingly important alternative to centralized control of production networks; however, achieving effective cooperation and choosing the appropriate level of autonomy are significant challenges in design of these autonomous logistic systems [2–4].

Due to the complexity of interactions between decision-making entities in production networks, modeling their behavior also is a challenge [5,6]. Two-level models have been developed that combine control of Work In Progress (WIP) with control of backlog [7] and final inventory [8]. Application of control theory to the production inventory problem has been reviewed [9], 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 [10]. Autonomous work systems require coupling structures that create the information-based interactions necessary to ensure that local actions are globally effective [11], and the control laws and heuristic rules chosen need to create well-behaved network dynamics including desired responsiveness, absence of oscillatory behavior, and robustness in the presence of uncertainties. There is a need to limit the propagation of disturbances in a production network and to ensure that the dynamic behavior of the network remains as designed and does not change unpredictably or unfavorably with time.

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It is shown in this paper, through dynamic system analysis, that when the structure of order flows between the work systems is omni-directional and variable, there can be variations in the fundamental dynamic behavior of the work systems and the production network. It is also shown that information coupling created by sharing of order-flow structure information can produce desired and consistent dynamic behavior when the order-flow information is accurate. A method for designing the dynamic properties of a network is presented along with a method for distributed computation and communication of information needed to locally compensate for the expected order flows from other work systems.

2. Dynamic model

The WIP regulation topology for autonomous work systems shown in Fig. 1 was analyzed in which order-flow information is shared to anticipate and compensate for the expected dynamic effects of physical order flows between work systems. The work systems adjust capacity with the objective of maintaining a desired amount of local WIP, a logistic variable that is readily measured [12]. The desired WIP can be locally specified or planned at a higher level by entities outside the network, and it need not be constant. It is assumed that local capacity is periodically adjusted, daily or weekly for example. T is the time period between capacity adjustments (for example, one shop calendar day). WIP is assumed to be regulated using adjustments in full capacity that are delayed by time dT, d time periods, representing the realities of labor contracts and other logistic issues that prevent instantaneous adjustment of capacity. Fig. 2 shows the dynamic model of a network of N work systems. Time-domain definitions of the vectors in the model, elements of which are shown in Fig. 1, are as follows:

$\mathbf{i}(kT)$ — actual rates at which orders are input to the work systems from sources external to the network;

$\mathbf{w}_d(kT)$ — work disturbances such as rush orders and order cancellations;

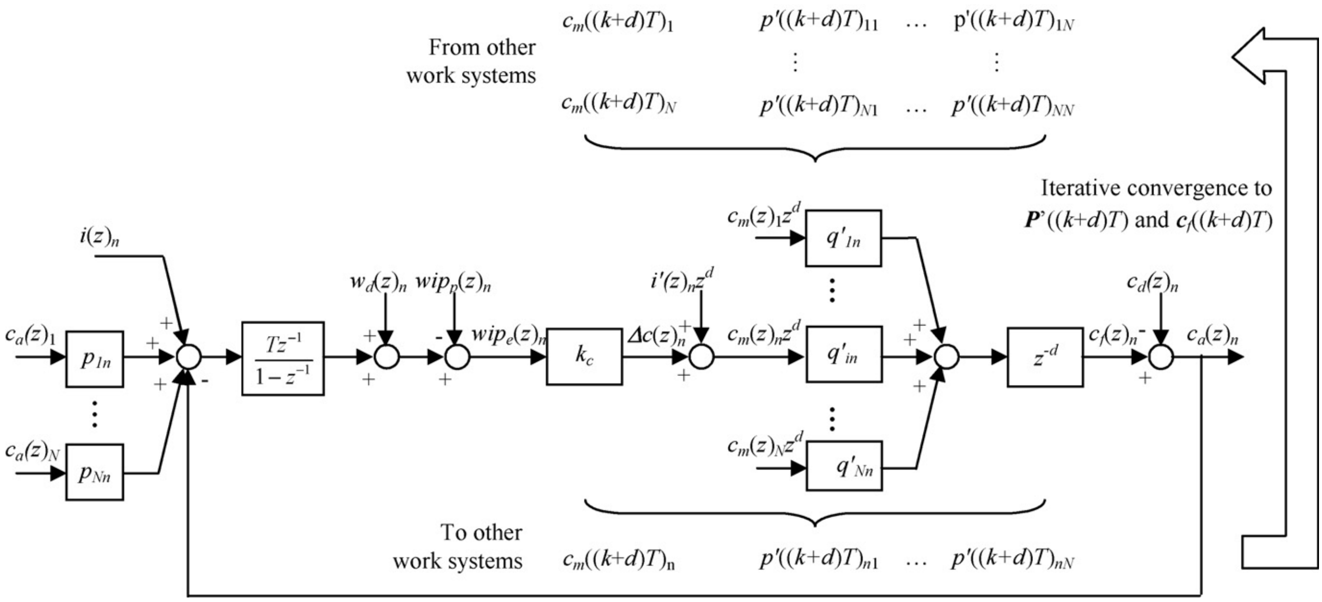

Fig. 1. WIP regulation in work system n, in which order-flow structure is cooperatively determined for the purpose of establishing and maintaining constant fundamental dynamic properties.

$\boldsymbol{wip}_p(kT)$	desired WIP;
$\mathbf{i}'(kT)$	expected input rates from sources external to the network;
$\mathbf{c}_f(kT)$	full capacity as determined by the capacity adjustment policy;
$\mathbf{c}_d(kT)$	capacity disturbances such as operator illness and equipment failure;
$\mathbf{c}_a(kT)$	actual capacity.

These represent continuous variables that are assumed to be constant over time $kT \leq t < (k+1)T$ where $k = 0, 1, 2, \ldots$ The total orders that have been input to and output from the work systems up to time kT are represented in the time domain by $\boldsymbol{w}_i(kT)$ and $\boldsymbol{w}_o(kT)$, respectively. Capacity limits, buffer size limitations, setup times, transportation times, variations in delay with capacity adjustment magnitude, etc. are not modeled. 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 [13]. The units of work are orders and the units of capacity are orders per shop calendar day (orders/scd).

The following also are assumed to be constant over time $kT \leq t < (k+1)T$: $\mathbf{P}'(kT)$, a matrix in which each element $p'(kT)_{nj}$ represents the expected fraction of the orders flowing out of work system n that flow into work system j; $\mathbf{P}(kT)$, a matrix in which each element $p(kT)_{nj}$ represents the actual fraction of the orders flowing out of work system n that flow into work system j; $\mathbf{P}_o(kT)$, a diagonal matrix in which element $p_o(kT)_{nn}$ represents the actual fraction of orders flowing out of work system n that flow out of the network. $\mathbf{P}(kT)$ and $\mathbf{P}_o(kT)$ represent the actual structure of order flow in the network. The information coupling between the work systems is represented by

$$\boldsymbol{Q}'(kT) = (\boldsymbol{I} - \boldsymbol{P}'^T(kT))^{-1} \tag{1}$$

The transfer equations relating $\boldsymbol{wip}_a(z)$ and $\mathbf{c}_a(z)$ to the inputs $\mathbf{i}(z)$, $\boldsymbol{w}_d(z)$, $\boldsymbol{wip}_p(z)$, $\mathbf{i}'(z)$ and $\mathbf{c}_d(z)$ when $\mathbf{P}'$, $\mathbf{P}$ and $\mathbf{P}_o$ are constant:

$$\begin{aligned}\boldsymbol{wip}_a(z) = {} & ((1-z^{-1})\boldsymbol{I} + k_cT(\boldsymbol{I}-\boldsymbol{P}^T)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}z^{-(d+1)})^{-1}(Tz^{-1}\boldsymbol{i}(z) \\ & + (1-z^{-1})\boldsymbol{w}_d(z) + k_cT(\boldsymbol{I}-\boldsymbol{P}^T)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}z^{-(d+1)}\boldsymbol{wip}_p(z) \\ & - T(\boldsymbol{I}-\boldsymbol{P}^T)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}z^{-1}\boldsymbol{i}'(z) + T(\boldsymbol{I}-\boldsymbol{P}^T)z^{-1}\mathbf{c}_d(z))\end{aligned} \tag{2}$$

$$\begin{aligned}\mathbf{c}_a(z) = {} & ((1-z^{-1})\boldsymbol{I} + k_cT(\boldsymbol{I}-\boldsymbol{P}^T)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}z^{-(d+1)})^{-1}(k_cT(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1} \\ & \times z^{-(d+1)}\boldsymbol{i}(z) + k_c(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}(1-z^{-1})z^{-d}\boldsymbol{w}_d(z) \\ & - k_c(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}(1-z^{-1})z^{-d}\boldsymbol{wip}_p(z)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}(1-z^{-1})\boldsymbol{i}'(z) \\ & - (1-z^{-1})\mathbf{c}_d(z))\end{aligned} \tag{3}$$

Fundamental dynamic properties of the network then are described by the roots of

$$det((1-z^{-1})\boldsymbol{I} + k_cT(\boldsymbol{I}-\boldsymbol{P}^T)(\boldsymbol{I}-\boldsymbol{P}'^T)^{-1}z^{-(d+1)}) = 0 \tag{4}$$

3. Selection of control parameter value

In Figs. 1 and 2, 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. While each work system could have a different value of this control parameter, here it is assumed to be the same throughout the

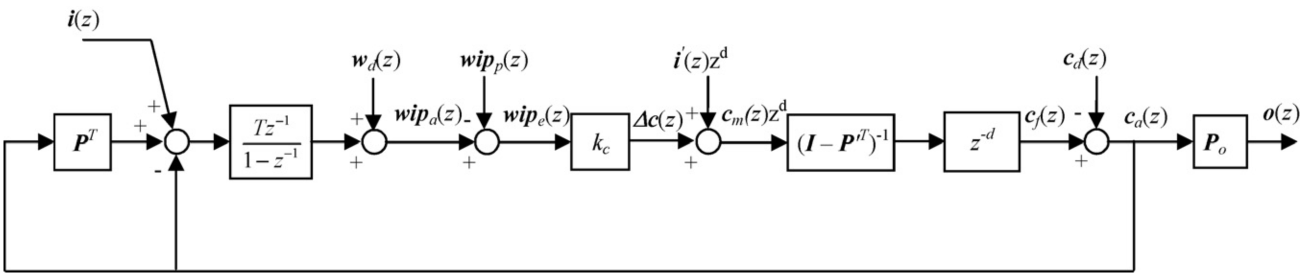

Fig. 2. WIP regulation in a network of autonomous work systems.