

# Assessment of fidelity of control-theoretic models of WIP regulation in networks of autonomous work systems

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## ABSTRACT

One means of adapting to variation in demand is making capacity flexible so that work in progress (WIP) can be regulated; however, this can significantly influence the dynamic behavior of production networks in which there is high local autonomy. Control-theoretic models are a convenient means for investigating and designing the dynamics of such networks, but the fidelity of these models is not well understood. In this paper, results obtained using discrete-event simulations are used to assess the control-theoretic approach, providing evidence that fidelity varies depending upon factors such as WIP level and the magnitude of capacity adjustments.

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## 1. Introduction

Industries are being continually challenged by variability due to product variety, shortened lead times, rush orders, etc. Industries have attempted to address these issues using concepts such as agile manufacturing, quick response manufacturing and lean manufacturing. Centralized control and information sharing has been recommended to reduce effects of variability in demand in production networks and unfavorable dynamic behavior such as the ‘bullwhip effect’ [1]. However, required information sharing and complexities due to growing numbers of echelons and relationships in networks complicates centralized control, and autonomous decentralized control has been recommended to better respond to changing markets [2,3]. As production networks expand and increase in complexity, it is important to ensure that local decision making and disturbances do not adversely affect their dynamic behavior [4].

Techniques and tools of control theory can be used to understand dynamics of production networks. A review of research in this area suggested that control theory can be used to reduce inventory variations, demand amplifications and optimize order release rules in the networks [5]. Industries often struggle with maintaining optimal work in progress (WIP) to satisfy conflicting objectives of short lead times and high utilization when there is high variability in demand [6]. Non-linear operation rules have been developed to adjust WIP in complex networks [7]. Control-theoretic models have been used to analyze stability of production networks [8], and recommended for regulating lead times and improving customer service [9]. Control-theoretic approaches have been proposed for WIP regulation to improve operating performance, and dynamic models have been developed for WIP regulation in networks of autonomous work systems [10–12].

Control-theoretic models of production networks can be developed more quickly than discrete-event simulation models, and produce estimates of fundamental dynamic properties such as time constants and damping ratios that characterize how rapidly production networks respond to turbulence and whether responses are oscillatory. However, the fidelity with which control-theoretic models predict the fundamental dynamic behavior of production networks is not well understood and has not been assessed. Many assumptions are required to make control-theoretic models tractable, and many details are ignored regarding the logistics of production. Such an assessment is described in this paper. A specific industrial scenario was used to assess the fidelity of a control-theoretic model of a network of autonomous work systems with local WIP regulation. A discrete-event simulation was developed for the same scenario and used as the benchmark for comparison. In the following sections, these models are described and areas of agreement and deviation are identified. The benefits of WIP regulation using a control-theoretic approach are also discussed.

## 2. Control-theoretic model

It was assumed in the control-theoretic model that was studied that work system capacity can be periodically adjusted.  $N$  work systems were assumed to be present in the production network. Setup times, transportation times and capacity and buffer limitations were not considered. A constant delay of  $d$  days was assumed in implementing change in capacity due to labor or other issues. Inputs were assumed to be constant during time  $kT \leq t < (k+1)T$ , where  $k=0, 1, 2, \dots$  and  $T$  is the time period between capacity adjustments. Input to the work systems at time  $(k+1)T$  was represented using the vector [12].

$$\mathbf{W}_i((k+1)T) = \mathbf{W}_i(kT) + T(\mathbf{i}(kT) + \mathbf{P}^T \mathbf{C}_a(kT)), \quad (1)$$

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where  $\mathbf{i}(kT)$  and  $\mathbf{C}_a(kT)$  represent input and output rates of the work systems, respectively.  $\mathbf{P}$  is a workflow matrix in which each element  $p_{nj}$  represents the fraction of work flowing from work system  $n$  to work system  $j$  during time  $kT \leq t < (k+1)T$ . Total output from the work systems until time  $(k+1)T$  is

$$\mathbf{W}_o((k+1)T) = \mathbf{W}_o(kT) + \mathbf{C}_a(kT)T \tag{2}$$

The WIP is

$$\mathbf{WIP}_a(kT) = \mathbf{W}_i(kT) - \mathbf{W}_o(kT) + \mathbf{W}_d(kT), \tag{3}$$

where  $\mathbf{W}_d(kT)$  represents disturbance inputs to the work systems such as rush orders. If the WIP in each work system is desired to be maintained at a planned level  $\mathbf{WIP}_p(kT)$ , then the change in capacity  $\Delta\mathbf{C}(kT)$  at the work systems can be adjusted with respect to planned capacity  $\mathbf{C}_p(kT)$  using a simple control law with proportional control constant  $K_c$ :

$$\Delta\mathbf{C}(kT) = K_c(\mathbf{WIP}_a(kT) - \mathbf{WIP}_p(kT)) \tag{4}$$

The actual capacity (production rate)  $\mathbf{C}_a(kT)$  is

$$\mathbf{C}_a(kT) = \mathbf{C}_p(kT) + \Delta\mathbf{C}((k-d)T) + \mathbf{C}_d(kT) \tag{5}$$

where  $\mathbf{C}_d(kT)$  represents disturbances in capacity.

The primary limitations of the control-theoretic model were:

- Individual orders and machines were not represented.
- Capacity and WIP could vary outside practical limits.
- Set up and transportation times were not represented.
- A constant work-flow matrix was used.

### 3. Discrete-event simulation

#### 3.1. Without WIP regulation

To assess the fidelity of the control-theoretic model, a discrete-event simulation (DES) model was developed using the commercial software ARENA, and an industrial dataset was used as the simulation scenario. This dataset was from a supplier to the automotive industry and it documented 659 orders that were processed in a 186-day period [13]. In the simulation, machines were grouped to form five work systems: Shearing/Sawing, Ring Rolling, Drop Forging, Heat Treatment and Quality Control as shown in Fig. 1. WIP was measured in hours of work.

Limitations of the DES model included:

- Labor was not considered as a resource.
- Set up and transportation times were not considered.
- Machine failures and downtime were not considered.
- Work on weekends was not considered.

The time when each order entered into the network and the service times at each work system were documented in the dataset and used in the simulation. The capacity of each work system was fixed at the average daily input in the dataset. Fig. 2 shows the WIP

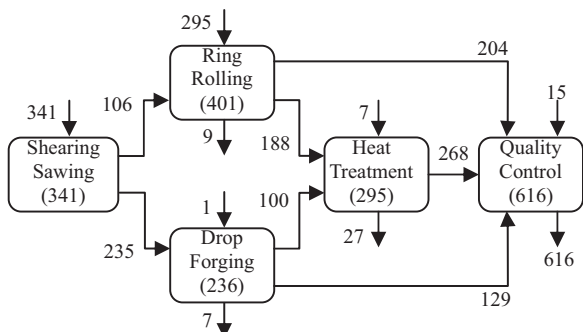


Fig. 1. Flow of orders in the network of work systems that was studied.

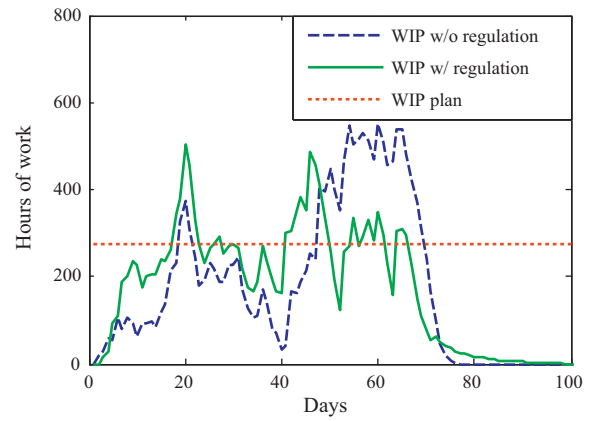


Fig. 2. WIP in the Drop Forging work system predicted by DES with and without WIP regulation.

Table 1 Mean WIP and variation in WIP with and without WIP regulation.

Work system	DES w/o WIP regulation		DES w/WIP regulation		% decrease in $\sigma$
	Mean	$\sigma$	Mean	$\sigma$	
Shearing/Sawing	153	52	153	41	23%
Ring Rolling	370	142	381	77	45%
Drop Forging	273	159	279	83	48%
Heat Treatment	110	59	116	51	14%
Quality Control	344	98	377	70	28%

Table 2 Mean lead time and variation in lead time with and without WIP regulation.

Work system	DES w/o WIP regulation		DES w/WIP regulation		% decrease in $\sigma$
	Mean	$\sigma$	Mean	$\sigma$	
Shearing/Sawing	54	36	54	31	16%
Ring Rolling	74	49	74	42	14%
Drop Forging	106	61	105	44	27%
Heat Treatment	53	40	49	34	15%
Quality Control	66	74	58	62	16%

predicted by this DES model for the Drop Forging work system. Variation in WIP was similar in the other work systems.

#### 3.2. With WIP regulation

Eqs. (4) and (5) were added to the DES to calculate capacity adjustments for the work systems for the purpose of regulating WIP. These adjustments were implemented by changing work-day length rather than the number of operating machines. The WIP predicted using  $K_c = 0.25 \text{ day}^{-1}$  in the Drop Forging work system is shown in Fig. 2. Average WIP found using DES without WIP regulation was used as the planned WIP, and average daily input also found using DES without WIP regulation was used as the planned capacity for each work system. The ramp up and ramp down periods were excluded in calculating averages. Table 1 shows that variation in WIP was reduced in all of the work systems by WIP regulation. Table 2 shows that variability in lead time was intrinsically reduced, even though service times varied significantly between orders, thus improving on-time deliveries and customer service.

### 4. Control-theoretic simulation

A control-theoretic simulation (CTS) model was implemented in Excel using Eqs. (1) through (5). Internal flow of orders was approximated using the workflow matrix shown in Table 3. These data were obtained from the DES without WIP regulation. WIP at the Shearing/Sawing work system predicted by CTS was the same

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