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ORIGINAL PAPER

Coordination of capacity adjustment modes in work systems with autonomous WIP regulation

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Abstract A method is presented in this paper for coordinating multiple modes of capacity adjustment in work systems with autonomous WIP regulation with the goal of maintaining desired fundamental dynamic behavior. To prevent overcorrection of capacity, adjustments involving floaters, temporary workers, overtime, etc. need to be coordinated, and it is shown that control-theoretic analysis can be used to develop algorithms for determining combinations of adjustments that result in WIP regulation that is as fast-acting as possible yet non-oscillatory. Results of discrete event simulations in Arena, driven by industrial data, are used to illustrate the dynamic behavior of WIP regulation in an autonomous work system that incorporates such an algorithm and multiple modes of capacity adjustment.

Keywords Capacity · Control · Dynamics

1 Introduction

With the increasing complexity and uncertainty in demand, as well as the rise of global competition that modern manufacturing industries face, superior control of internal processes is an attribute that companies strive for in order to maintain a competitive "edge." Work-In-Progress (WIP) regulation is an important aspect of this, with objectives of high utilization and keeping lead times short. It has been suggested that optimization of these conflicting objectives can be approached using the concept of ideal minimum WIP [1]. If WIP deviates from this ideal, or some multiple of it, then loss of performance occurs in the form of lower utilization or higher lead times. Regulation of WIP, in the presence of turbulence in demand, requires flexible capacity; the agility with which capacity can be adjusted is a crucial factor.

Beyond simply hiring or laying off permanent employees, several modes of capacity adjustment may be available to manufacturing industries. Each has its positive and negative aspects as well as specific constraints. The use of "floaters" is common. Floaters are cross-trained workers who are able to perform a variety of tasks within a company. In a manufacturing environment, they may be assigned to a different department each day, or assignment changes may occur even more frequently. These personnel are useful for filling in for absent workers or increasing the capacity of a work system that has accumulated backlog. However, training costs are generally higher for these higher-skilled workers and depend on the quantity and difficulty of the tasks they are expected to perform. In addition, the number of these workers available is often limited because they come from within the company. Wild and Schneeweiss presented a hierarchical approach for capacity planning with decisions made at long-, medium-, and short-term levels [2]. In their model, every seventh worker is "highly qualified" (i.e., a floater).

The utilization of temporary workers is a second potential mode of capacity adjustment. Temporary workers are extra personnel recruited to increase the available amount of labor and are not part of the primary workforce. Foote and Folta described an appropriate situation for their employment: "heavy use of temporary workers for

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uncertain expansion projects allows the firm to quickly adjust its workforce in response to worsening or improving economic conditions at negligible cost relative to adjustments involving permanent employees" [3]. Temporary workers may be hired directly by the company in need or dispatched from an agency to a client organization where the work is carried out. Companies that work closely with temporary employment agencies may be able to obtain a large number of workers very quickly depending on the size and experience of the agency. However, these temporary workers are not part of the primary workforce, and additional coordination by management or experienced employees may be needed to achieve effective performance; these temporary workers may require training on specific company processes and policies. Although this mode of capacity adjustment often has only a short delay, floaters usually allow for a quicker response.

In many companies, overtime is an important mode of adjusting capacity, which is achieved by adjusting the work hours of existing employees [4]. By having permanent employees perform their known tasks, the costs of training new employees can be avoided, along with fringe benefits and other costs of hiring and layoffs. However, hourly workers often must be paid at a multiple of their usual rate for time worked above a normal work day or work week. If overtime is occurring frequently, it may be preferable to hire additional permanent employees. Also, requiring workers to work longer hours can cause physical and psychological strain, and union rules may place constraints on who can work overtime and for how long.

For companies that need larger capacity adjustments, employees can be hired or laid off, and the number of working shifts can be changed. Hiring additional permanent workers typically implies higher hiring and training costs, and the company may be "locked-in" for a longer period of time with this mode of capacity adjustment. Hence, careful planning is required, and there usually is a longer delay in implementing such capacity adjustments than with the other modes discussed above. It is important to consider the economics of each mode of capacity adjustment: training costs may be high for companies that employ many floaters, but companies that utilize overtime face other expenses and potential negative effects on workers.

More than one mode of capacity adjustment can be used by a company to regulate WIP. For example, if WIP is higher than desired, then floaters could be immediately assigned to increase work system capacity up to a limit; then, if additional capacity is required, overtime could be used, up to a limit, with some delay in implementation. To prevent overcorrection, such capacity adjustments cannot be made independently, and an appropriate decision-making algorithm must be employed by managers with responsibility for control of internal processes. Delays in implementation associated with the various modes of capacity adjustment, and limits on the magnitudes of the adjustments that can be made, complicate these algorithms and can significantly affect the dynamic behavior of the production system employing them. The tools of control theory can assist in devising algorithms for determining combinations of capacity adjustments that result in WIP regulation that has desirable fundamental dynamic behavior, for example, responses to turbulence that are as fast-acting as possible, yet non-oscillatory.

In the following sections of this paper, an example of a capacity adjustment algorithm will be presented that coordinates capacity adjustments between two adjustment modes in work systems with autonomous WIP regulation [5]. The coordination algorithm is based on the characteristic equation obtained using control-theoretic analysis of WIP regulation. It specifies how the control parameters (gains) for each mode of capacity adjustment are varied as limits in capacity adjustment are reached. The method used in the example can be applied to work systems with various capacity adjustment modes, various combinations of adjustment frequencies, and various delays in implementing adjustments. Results of discrete event simulations in Arena, driven by industrial data, are presented that illustrate the dynamic behavior of WIP regulation in an autonomous work system that incorporates the two modes of capacity adjustment and the coordination algorithm. Measures of variation in capacity and WIP are used to compare results and justify presented conclusions.

2 Control-theoretic coordination of capacity adjustment

Control-theoretic dynamic models have been previously developed for work systems with autonomous WIP control [6–8] that incorporates various capacity adjustment periods and delays. While it is outside the scope of this paper to review these general methods, results are presented for a capacity adjustment scenario that combines two modes: no delay in adjustment; and 1-day delay in adjustment. These could be implemented, for example, by the combination of same-day adjustment using floaters and next-day adjustment using temporary workers. It is assumed that WIP in the work system is measured at the beginning of each work day, and capacity adjustments are implemented at the beginning of each work day as determined using present and past deviations of WIP from what is planned.

In the no-delay mode, capacity adjustment decisions (by what quantity to increase or decrease the capacity) are made each work day, and there is no delay in implementation of these decisions. For example, WIP can be measured each morning and appropriate capacity adjustments are immediately implemented. In the 1-day delay mode, capacity adjustment decisions are made each work day, but implementation is delayed by one work day. The equations used for adjusting capacity at time nT, where n is a positive integer and T is the period of time between capacity adjustments (1 day in this example), are

$$c_a(nT) = c_p(nT) + \Delta c(nT) \tag{1}$$

$$\Delta c(nT) = k_0(nT)\big(WIP_a(nT) - WIP_p(nT)\big) + k_1(nT)\big(WIP_a((n-1)T) - WIP_p((n-1)T)\big) \tag{2}$$

where $c_a(nT)$ is the adjusted capacity, $c_p(nT)$ is the planned capacity, $\Delta c(nT)$ is the capacity adjustment, $WIP_a(nT)$ and $WIP_a((n\text{-}1)T)$ are the current and previous measured WIP, $WIP_p(nT)$ and $WIP_p((n\text{-}1)T)$ are the current and previous planned WIP, and $k_0(nT)$ and $k_1(nT)$ are WIP-regulation parameters (units time^{-1}) selected to maintain desirable fundamental dynamic behavior. The following discrete characteristic equation describes the fundamental dynamic properties of the work system with WIP regulation:

$$z^2 - (1 - k_0T)z + k_1T = 0 \tag{3}$$

Figure 1 shows the relationship between k_0T and k_1T and the percent overcorrection in capacity adjustment that is represented by this characteristic equation, while Fig. 2 shows the relationship between these two parameters and normalized settling time T_s/T in response to turbulence. (Here, settling time has been calculated using the equivalent damping ratio and natural frequency.) The line of equivalent constant damping ratio $\zeta = 1$ is shown on both figures. For example, when $k_0T = 0$, $k_1T = 0.25$ there is no overcorrection, whereas when $k_0T = 1$, $k_1T = 0.25$ the overcorrection is approximately 20 %. This line indicates the combinations of k_0T and k_1T in Eqs. (2) and (3) that produce response to turbulence that is as rapid as possible without producing overcorrection (overshoot) in capacity adjustments.

The combination $k_0T = 1$, $k_1T = 0$ produces the most desirable response; however, the amount of capacity

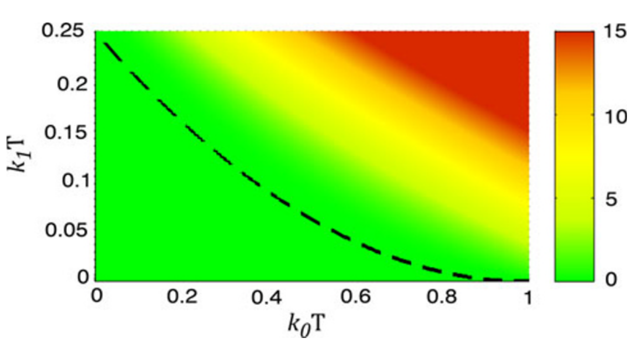

Fig. 1 Percent overcorrection in capacity adjustment versus k_0T and k_1T

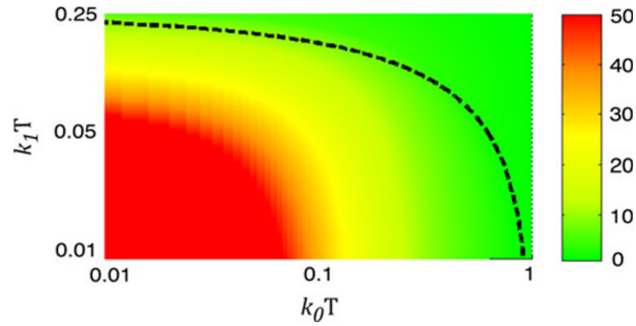

Fig. 2 Normalized settling time T_s/T in response to turbulence versus k_0T and k_1T

adjustment in the no-delay mode (for example, the number of floaters that can be added or removed from the work system) is often limited. In this case, the following algorithm can be used to determine k_0 and k_1 given capacity adjustment period T:

$$k_0(nT) = \frac{1}{T} \tag{4}$$

$$k_1(nT) = 0 \tag{5}$$

$$\Delta c_0(nT) = k_0(nT)\big(WIP_a(nT) - WIP_p(nT)\big) \tag{6}$$

If

$$|\Delta c_0(nT)| > \Delta c_{0_{max}} \tag{7}$$

then

$$k_0(nT) = \frac{\Delta c_{0_{max}}}{|\Delta c_0(nT)|T} \tag{8}$$

and

$$k_1(nT) = \frac{(1 - k_0(nT)T)^2}{4T} \tag{9}$$

$$\Delta c_1(nT) = k_1(nT)\big(WIP_a((n-1)T) - WIP_p((n-1)T)\big) \tag{10}$$

where $\Delta c_{0\max}$ is the maximum capacity adjustment that can be made with no delay (for example, the maximum number of floaters) and

$$k_1(nT)T < 0.25 \tag{11}$$

There also can be a limit $\Delta c_{1\max}$ on the capacity adjustment that can be made with 1-day delay, and application of this limit can be readily added to this algorithm.

3 Simulation of coordinated of capacity adjustment

The algorithm for coordination of capacity adjustment modes described in the previous section was studied using

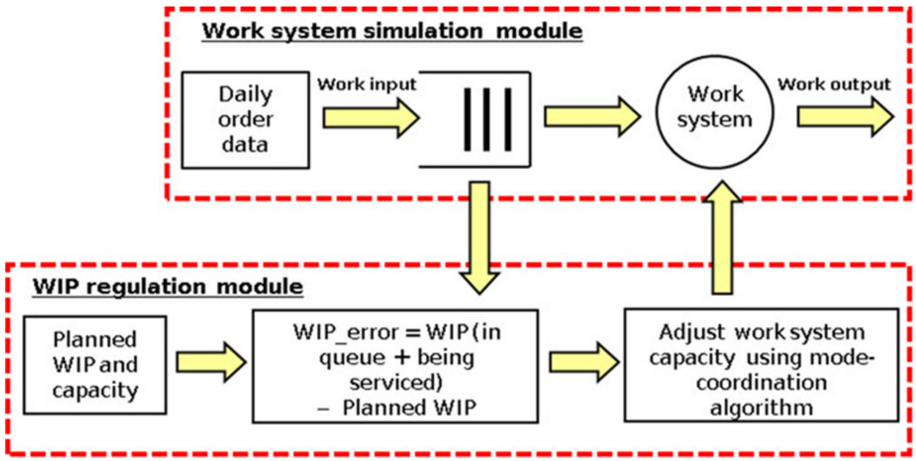

Fig. 3 Discrete event simulation of work system with autonomous WIP regulation

a discrete event simulation driven by input from a real-world industry dataset. These data were from a supplier to the automotive industry. The dataset contains the orders received and processed over a period of approximately 3 months. Details include order numbers, machines, order start dates, target order times, actual order times, and lot sizes. A significant fraction of the documented orders were processed on shearing and sawing machines as the first step in their production. For the purpose of the research reported here, these machines were grouped as a Shearing/Sawing work system and the data associated with them were examined. Some of the work in this work system was done on weekends, but the amount of work was quite small, and to simplify simulations and clarify results this work was shifted to the following Monday. No setup times for orders or machines were provided in the dataset, nor was failure and preventative maintenance information. Because there were large variations in both work content from order to order and orders arriving day to day, there were large daily variations in work input to the work system. These variations represented turbulence to which the work system was required to react by making capacity adjustments for the purpose of regulating WIP.

In addition to the provided data, several key parameters were needed for simulating autonomous WIP regulation in the Shearing/Sawing work system. The planned capacity c_p for the work system was assumed to be constant and was calculated as the average daily work input, which was 49.95 hours/day. The planned WIP for the work system was assumed to be the average of the WIP in the data, which was 384 h. Investigation of the effects of planned WIP on utilization and work system dynamic behavior was outside the scope of this work. (see Toshniwal [9] for more information on this production system, its behavior as a function of WIP, and the characteristics of the work input data).

The discrete event simulation model of the Shearing/Sawing work system was constructed using Arena. As indicated in Fig. 3, there were two main modules in the model: a work system simulation module; and a WIP-regulation module [9]. At 8:00 am each workday, the (current) WIP (the sum of work in a single work-system queue and work remaining in orders being serviced on machines in the work system) was measured and capacity adjustments were calculated. The work system had six machines and one input queue. There were no limits on queue size, and set up and transportation times were neglected. In the following subsections, simulation results are presented that first illustrate the behavior of the individual modes of capacity adjustment and then illustrate the behavior of the coordination of the two modes using the algorithm described in the previous section.

3.1 No delay in capacity adjustment

Figure 4 shows simulation results for WIP and work system capacity when there is no delay in capacity adjustment ($T = 1$ day, $k_0 = 1$ day^{-1}, $k_1 = 0$ day^{-1}) and no limit on the magnitude of adjustment. The initial "ramp up" and final "ramp down" portions of the simulation results are not included in performance measurements. In this case, WIP is well regulated, but capacity adjustment magnitudes are large. The standard deviation of capacity and WIP are shown in Table 1.

3.2 1-day delay in capacity adjustment

Figure 5 shows the simulation results for WIP and work system capacity when there is a 1-day delay in capacity adjustment ($T = 1$ day, $k_0 = 0$ day^{-1}, $k_1 = 0.25$ day^{-1}) and no limit on the magnitude of adjustment. In this case,

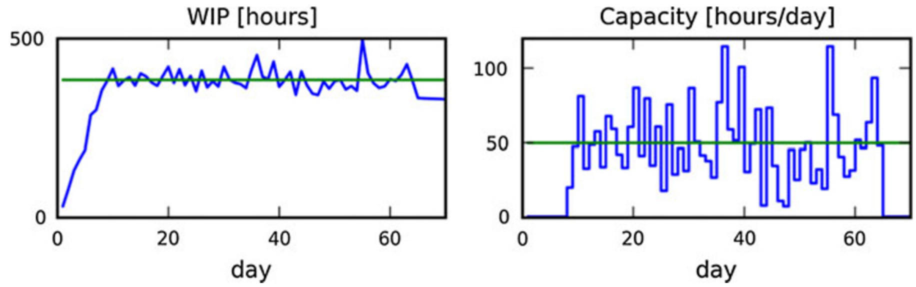

Fig. 4 WIP and capacity with $T = 1$ day, $k_0 = 1$ day^{-1}, $k_1 = 0$ day^{-1}

Table 1 Standard deviation of capacity and WIP obtained from discrete simulations with no limits on capacity adjustments and no coordination between modes

Mode	No delay	1-day delay	No delay + 1-day delay
k_0 (day^{-1})	1	0	1
k_1 (day^{-1})	0	0.25	0.25
σ_{cap} (hours/day)	4.19	1.80	4.57
σ_{WIP} (hours)	28.27	44.32	29.22

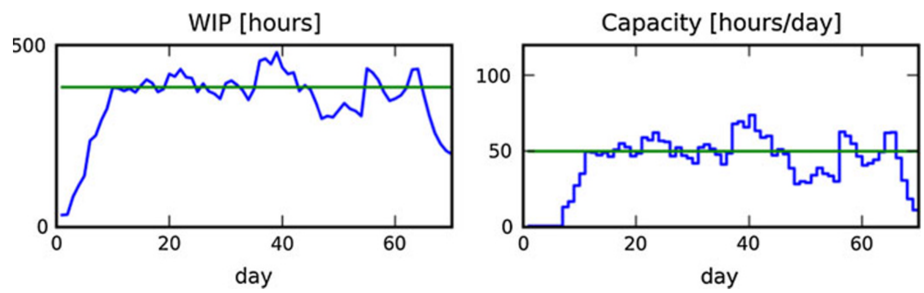

Fig. 5 WIP and capacity with $T = 1$ day, $k_0 = 0$ day^{-1}, $k_1 = 0.25$ day^{-1}

WIP regulation is not as effective as in the no-delay case, but capacity adjustment magnitudes are reduced. Again, the standard deviation of capacity and WIP are shown in Table 1.

3.3 Combination of capacity adjustment modes without coordination

When the no-delay and 1-day delay modes are combined without using the algorithm described in Sect. 2 ($k_0 = 1$ day^{-1}, $k_1 = 0.25$ day^{-1}), the standard deviations of capacity adjustment and deviation of WIP from planned WIP that result are shown in Table 1. Deviations in both capacity and WIP are increased with respect to the no-delay case because there is overcorrection in capacity adjustments as predicted by Fig. 1.

3.4 Coordination of no-delay and 1-day delay in capacity adjustment

In reality, there are limits on the magnitude of capacity adjustment that are possible in each mode. Therefore, WIP-regulation parameters k_0 and k_1 can be adjusted according to the algorithm described in Sect. 2, which incorporates limits while avoiding overcorrection of capacity. Figure 6 shows the simulation results for WIP and work system capacity when there is a 12-hours/day limit on no-delay capacity adjustment ($T = 1$ day, $\Delta c_{0\max} = 12$ hours/day), and Fig. 7 shows the capacity adjustments and WIP-regulation parameters generated by the algorithm.

Table 2 shows the results of applying this algorithm with various limits on magnitude of no-delay capacity adjustments. It can be observed, as expected, that deviation in WIP decreases and deviation in capacity increases as larger no-delay capacity adjustments are permitted. The variation in capacity is significantly less than that shown in Table 1 for the case without coordination between the two modes of capacity adjustment.

4 Conclusions

Consideration of dynamic behavior is important in designing agility into production systems that must respond effectively to turbulence in demand and capacity. A method for capacity adjustment coordination between

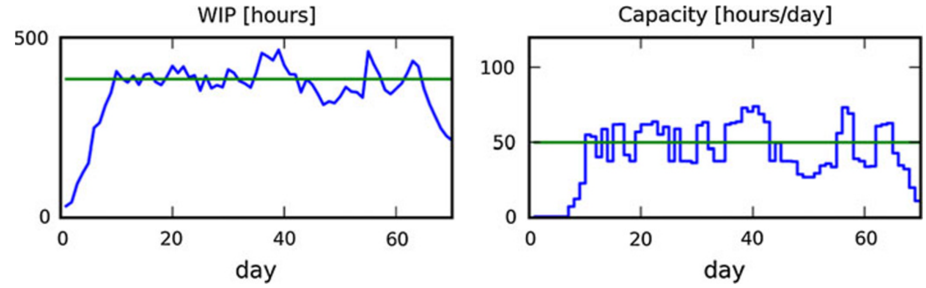

Fig. 6 WIP and capacity with $T = 1$, $\Delta c_{0\max} = 12$ hours/day

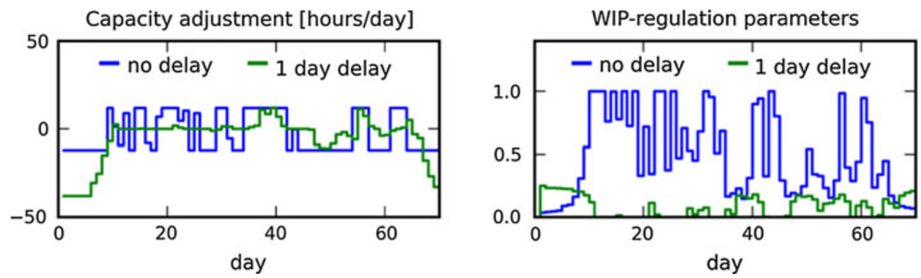

Fig. 7 Capacity adjustments and WIP-regulation parameter adjustments with $T = 1$, $\Delta c_{0\max} = 12$ hours/day

Table 2 Mean capacity adjustments and standard deviation of capacity and WIP obtained from discrete simulations for various values of capacity adjustment limit $\Delta c_{0\max}$

$\Delta c_{0\max}$ (hours/day)	6	12	24	36
$\overline{\Delta c_0}$ (hours/day)	5.76	11.38	18.58	22.64
$\overline{\Delta c_1}$ (hours/day)	7.34	4.55	1.47	0.80
σ_{cap} (hours/day)	1.92	2.40	3.22	3.78
σ_{WIP} (hours)	40.10	35.96	31.14	29.34

various modes of capacity allocation adjustment has been described that maintains constant dynamic damping while using faster-acting modes first, up to their capacity adjustment limit, and then using slower-acting modes. The algorithm is based on results of control-theoretic analysis of WIP regulation. The algorithm for no delay paired with 1-day delay was presented, but similar capacity adjustment algorithms can be obtained for more complex combinations using similar analytical methods: an algorithm for coordinating no delay, 2-day delay, and 1-week delay capacity adjustments for example. Economic factors have not been incorporated into the algorithms, which are designed to eliminate overcorrection of capacity and accommodate limits on the magnitudes of capacity adjustments that can be implemented. The trade-off between variation in WIP and variation in capacity is not optimized, but overcorrection of capacity is prevented.

Results of discrete event simulations in Arena, driven by industrial data, were used to illustrate the dynamic behavior of WIP regulation in an autonomous work system that incorporates two modes of capacity adjustment. The results show that the approach that has been presented produces adaptive WIP regulation that avoids both overcorrection of velocity and sluggish response in work input that has significant turbulence. The results confirm the desirability of coordination of modes of capacity adjustment and confirm the fundamental dynamic behavior predicted by control theory.

References

1. Nyhuis P, Weindahl H-P (2009) Fundamentals of production logistics: theory. Tools and Applications Springer, Berlin
2. Wild B, Schneeweiss C (1993) Manpower capacity planning—a hierarchical approach. Int J Prod Econ 30–31:95–106
3. Foote DA, Folta TB (2002) Temporary workers as real options. In: Human resources management review, vol. 12, pp 579–597
4. Delarue A, Gryp S, Hootegem GV (2006) The quest for a balanced manpower capacity: different flexibiliy strageies examined. In: Enterprise and work innovation studies, vol. 2, pp 69–86
5. Windt K, Hülsmann M (2007) Changing paradigms in logistics—understanding the shift from conventional control to autonomous cooperation and control. In: Hülsmann M, Windt K (eds) Understanding autonomous cooperation and control in logistics. Springer, Berlin, pp 1–16
6. Duffie NA, Shi L (2009) Maintaining constant WIP-regulation dynamics in production networks with autonomous work systems. CIRP Annal Manuf Technol 58(1):399–402
7. Duffie N, Shi L (2010) Dynamics of WIP regulation in large production networks of autonomous work systems. IEEE Transact Autom Sci Eng 7(3):665–670
8. Toshniwal V, Duffie N, Jagalski T, Rekersbrink H, Scholz-Reiter B (2011) Assessment of fidelity of control-theoretic models of WIP regulation in networks of autonomous work systems. CIRP Annal Manuf Technol 60(1):485–488
9. Toshniwal V (2011) Assessment of WIP regulation in networks of autonomous work systems. Madison, M.S. Thesis, University of Wisconsin-Madison