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Optimal Dynamic Behavior of Adaptive WIP Regulation with Multiple Modes of Capacity Adjustment

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Abstract

It is desirable to maintain consistent dynamic behavior of WIP regulation in work systems with multiple modes of capacity adjustment (floaters, overtime, etc.) and different adjustment periods, delays and limits in the various modes. Coordination of these modes is necessary in order to keep optimal dynamic behavior. In this paper, a control-theoretic model of WIP regulation is presented first that accommodates multiple capacity adjustment modes with different adjustment periods (per shift, per day, per week, etc.) and different delays in implementing adjustments. Then an algorithm is presented for adapting WIP adjustment parameters in the presence of capacity adjustment limits and mode priorities so that a specified dynamic performance goal continues to be met. Results of simulations driven by industrial data are used to illustrate the effect of limits and performance goals on dynamic behavior, and conclusions are drawn regarding the effectiveness of adaptive regulation of WIP by coordinating multiple modes of capacity adjustment.

Keywords: WIP Regulation; Capacity Adjustment; Control Theory

1. Introduction

To be competitive, manufacturers need to adapt to increasingly dynamic market forces and employ production strategies that respond to turbulent conditions with robustness, timeliness and agility [1]. Flexible capacity can be a significant factor in enabling manufacturers to meet logistic targets such as due date reliability under fluctuating demand conditions while making effective use of production personnel [2,3]. Several modes of capacity adjustment usually are available: floaters typically can be reassigned to a variety of jobs or to different departments on short notice, but the number of floaters is often limited [4]; temporary workers can be hired or released on relatively short notice to increase or decrease the workforce, but their training can be a limiting factor [5]; overtime and its opposite, undertime, utilize permanent employees who perform their known tasks [6], but work rules and worker health and safety issues can limit which employees' working days can be modified, by how many hours they can be modified, and how much advance notice is required; permanent employees can be hired or laid off, but layoffs are often legally restricted and hiring permanent employees typically requires a long-term economic commitment; and working shifts can be added or eliminated, but there is a limit of three working shifts and there can be a long time delay in implementation. Each mode of capacity adjustment has its own costs, magnitude limitations and implementation delays. More capacity adjustment modes and less restrictive capacity adjustment limits result in greater flexibility and agility [7].

Coordination of capacity adjustments modes can significantly improve work system dynamic behavior. However, coordination is complex when adjustment periods of modes are not the same, priority is to be given to modes in which capacity can be adjusted more frequently, lower priority modes are to be used when capacity adjustment limits

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are reached for higher priority modes, and specific dynamic performance goals must be continually met. In this paper, previous work [8] is extended to show that Work-In-Progress (WIP) can be adaptively regulated in the presence of this complexity. A multi-rate control theoretic model is presented first for a work system that has two capacity adjustment modes that are adjusted with different periods, different limits and different amounts of implementation delay. In the first mode, floaters are used to adjust capacity without delay at the beginning of each of three shifts. In the second mode, overtime is adjusted daily with a 1-day delay. Then, an algorithm is presented for coordinating adjustments using these two modes in the presence of capacity adjustment limits, adapting WIP regulation to the present logistic situation using two different dynamic performance goals: achieving a critically damped response; and minimizing the first norm of the WIP deviation. Results from simulations driven by industrial data for different capacity adjustment limits and dynamic performance goals are then presented. These results are evaluated and compared and, finally, conclusions are drawn and recommendations are given for further research.

2. Dynamic analysis of WIP regulation

Coordination of capacity adjustment modes plays an important role in regulating WIP to be as close as possible to a planned level of WIP, which is chosen to obtain the best combination of high utilization and short lead times [9]. It has been shown in previous research [8] that adaptive WIP regulation can avoid both overcorrection of capacity and sluggish behavior when there are multiple modes of capacity adjustment, and control-theoretic dynamic models have been previously developed for autonomous work systems with WIP regulation [8,10–12]. In [8] a work system was modeled in which two modes of daily capacity adjustment were combined for the purpose of regulating WIP in the presence of demand fluctuations and capacity adjustment limits. The two modes were coordinated to avoid over adjustment of capacity on one hand and slow dynamic response to demand fluctuations on the other hand. Discrete event simulations confirmed the desirability of capacity adjustment coordination and the dynamic behavior that was predicted using control theory. However, modes of capacity adjustment do not, in general, have the same period between adjustments (adjustment in a particular mode can be per shift, per day, per week, etc.). Furthermore, some over adjustment of capacity can improve performance, for example, when it is desired to minimize deviations over time of WIP from planned WIP.

3. Control theoretic work system multi-rate model

The work system with WIP regulation that was studied had two modes of capacity adjustment. Up to $\pm\Delta c_{0\max}$ hours per shift of floaters can be assigned to the work system (or de-assigned) at the beginning of each of three shifts without delay in implementation of the assignment. Furthermore, up to $\pm\Delta c_{3\max}$ hours per day of overtime can be assigned, with a 1-day delay in implementation. The total capacity [hours/shift] of the work system is

$$c(t) = c_p(t) + \Delta c_0(t) + \Delta c_3(t) - c_d(t) \tag{1}$$

where $c_p(t)$ is the planned capacity, which was assumed to be constant during each shift. $c_d(t)$ represents any capacity disturbance such as worker illness or equipment failure, and $\Delta c_0(t)$ and $\Delta c_3(t)$ are the capacity adjustments made in the floater mode and overtime mode, respectively. The total work input to and output by the work system are $w_i(t)$ and $w_o(t)$ [hours], respectively:

$$w_i(t) = \int i(t)\,dt \tag{2}$$

$$w_o(t) = \int c(t)\,dt \tag{3}$$

where $i(t)$ is the rate of work input to the work system [hours/shift]. The WIP in the work system and also the WIP error (deviation from planned WIP) are

$$wip(t) = w_i(t) - w_o(t) + w_d(t) \tag{4}$$

$$wip_e(t) = wip(t) - wip_p(t) \tag{5}$$

where $w_d(t)$ represents any work disturbance such as rush orders or order cancellations, and $wip_p(t)$ is the planned WIP.

In the floater mode, WIP is measured at the beginning of each shift, and associated capacity adjustments are immediately calculated and implemented using

$$\Delta c_o(nT) = k_0(nT)wip_e(nT) \tag{6}$$

where n is a positive integer and T is the period of time between floater capacity adjustments (1 shift). $k_0(nT)$ is the floater capacity adjustment gain, which is adapted to the current logistic situation at each time nT by the coordinated capacity adjustment algorithm. $\Delta c_0(nT)$ is assumed to be held constant for the period T after it is calculated.

In the overtime mode, WIP is measured at the beginning of each day (the beginning of the first shift), and associated capacity adjustments are immediately calculated using

$$\Delta c_3(m3T) = k_3(m3T)wip_e(m3T) \tag{7}$$

where m is a positive integer and $3T$ is the period of time between overtime capacity adjustments (1 day). $k_3(nT)$ is the overtime capacity adjustment gain, which is determined at each time $m3T$ by the coordinated capacity adjustment algorithm. $\Delta c_3(m3T)$ is delayed by period $3T$ after it is calculated and held constant for a second period $3T$. Fig. 1 summarizes the model, which is multi-rate because there are two WIP measurement and capacity adjustment periods, T and $3T$.

The multi-rate system in Fig. 1 can be analyzed using sampler decomposition [13]. For example, the transfer equation for WIP measured at the beginning of each day is

$$wip_{e_{3T}}(z) = \frac{1-(1-k_0T)^3z^{-1}}{1-(1-k_0T)^3z^{-1}+k_3T(2-k_0T+(1-k_0T)^2)z^{-2}}x_{3T}(z) \tag{8}$$

where k_0 and k_3 are assumed to be constant, and $x_{3T}(z)$ is the Z transform [14] of the contributions of $i(t)$, $wip_p(t)$, $wip_d(t)$, $c_p(t)$ and $c_d(t)$ to WIP deviation $wip_e(m3T)$. The corresponding characteristic equation is

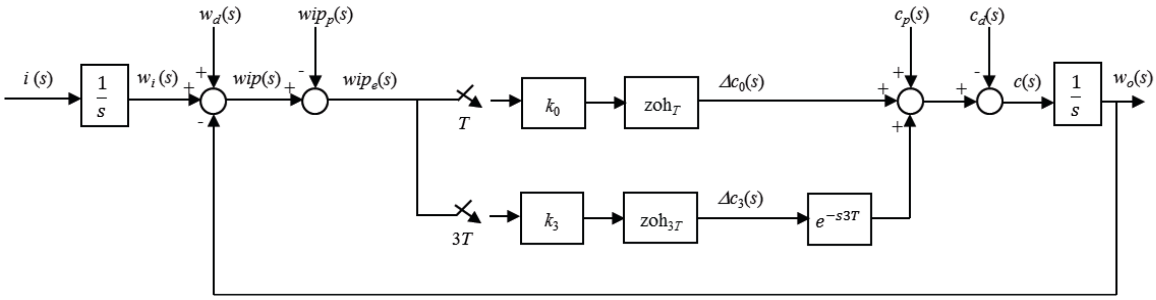

Fig. 1. Work system multi-rate model (T = 1 shift, $3T$ = 1 day)

$$z^2 - (1 - k_0T)^3 z + k_3T(2 - k_0T + (1 - k_0T)^2) = 0 \quad (9)$$

The choice of k_0 and k_3 and their adaptation using the coordinated capacity adjustment algorithm significantly affect the dynamic behavior of the system.

4. Coordinated capacity adjustment algorithm

In the absence of capacity adjustment limits, the best choice of capacity adjustment gains is $k_0T = 1$ and $k_3T = 0$. In this case, floaters completely adapt the work system to fluctuations in demand, and no overtime is required. However, floater capacity adjustments are subject to limits, and thus the effective adjustment gains are also subject to limits. Therefore, given a dynamic performance goal, k_0 and k_3 need to be selected to keep capacity adjustments within limits, yet produce optimal dynamic behavior.

Coordination of capacity adjustments requires prioritization of the capacity adjustment modes that are available. Capacity adjustments are made first with the highest priority mode and then using the other modes in the order of their priority. However, because some modes have longer periods between adjustments than other modes, the choice of capacity adjustment gains for shorter period modes must be restricted during these longer periods to ensure that the work system continues to meet the specified performance goal.

The coordinated capacity adjustment algorithm that was used is summarized in Fig. 2. Floater adjustments have the highest priority and are made at the beginning of each shift. On the other hand, overtime adjustments are made daily; hence, with three shifts per day, there are two possibilities for capacity adjustments:

Beginning of a day (1st shift)

In this case WIP is measured and capacity is adjusted at the beginning of the first shift, and the floater capacity adjustment is calculated first assuming $k_0T = 1$ and $k_3T = 0$. However, if the calculated floater capacity adjustment exceeds its limit, the value of k_0 is recalculated so that it produces a floater capacity adjustment equal to the limit. If k_0 has been recalculated, the optimal overtime capacity adjustment gain k_3 is calculated using the given dynamic performance goal. Then, if the calculated overtime capacity adjustment exceeds its limit, the value of k_3 is recalculated so that it produces an overtime capacity adjustment equal to the limit.

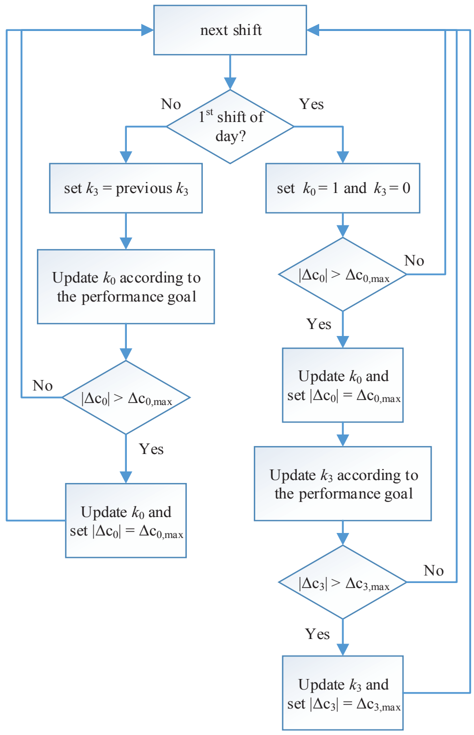

Fig. 2. Coordinated capacity adjustment algorithm

Not the beginning of a day (2nd and 3rd shifts)

In this case WIP is measured and capacity is adjusted at the beginning of a shift other than the first shift, and the overtime capacity adjustment gain k_3 already has been fixed at the beginning of the day (at the beginning of the first shift). The floater capacity adjustment gain k_0 is then calculated given the dynamic performance goal. Then, if the calculated floater capacity adjustment exceeds its limit, the value of k_0 is recalculated so that it produces a floater capacity adjustment equal to the limit.

The two dynamic performance goals that were used in the simulations are described in the following subsections.

4.1. Desired damping ratio

The first dynamic performance goal that was studied is based solely on the fundamental dynamic behavior described by Eqn. 9. The damping ratio ζ is a dimensionless measure that describes how dynamic systems respond to a disturbance: ζ<1 indicates fundamentally oscillatory capacity adjustment behavior, with magnitude of oscillation increasing as ζ decreases. Capacity adjustment gains k_0 and k_3 in Eqn. 9 directly affect the damping ratio as illustrated in Fig. 3. Furthermore, k_0 and k_3 and hence ζ directly affect the magnitude of oscillations, as measured by percentage overshoot of capacity beyond an equilibrium value, as well as the settling time required for capacity oscillations to damp out as illustrated in Figs. 4 and 5, respectively. Eqn. 9 can be used to select the values k_0 and k_3 that result in a system with a desired damping ratio ζ and hence the desired amount of overshoot (capacity over adjustment). Here, damping ratio ζ=1 is used as the dynamic performance goal. This produces a system with the shortest settling time (quickest response to changes in demand, but with no capacity overshoot). In general, however, this does not optimize the overall WIP deviations that result from a demand or capacity disturbance.

4.2. Minimum sum of absolute error in step response

Other dynamic performance goals minimize deviations over a period of time that result from a disturbance. Typically, a sum of either absolute values or squares of deviations is minimized, and the deviations can be weighted by time if desired to penalize longer lasting deviations. The second dynamic performance goal that was studied minimizes the sum of absolute values of deviations between actual work system WIP and the planned WIP over a specified period of time, deviations that result from a step change in demand. The function that is minimized is

$$\|E\|_1 = \sum_{n=1}^{N} |wip_e(nT)| \qquad (10)$$

where N is the number of shifts over which the function is evaluated. In general, response with some capacity overshoot produces the minimum. The values of capacity adjustment gains k_0 and k_3 are found by minimizing $\|E\|_1$ by iteratively simulating response to a step change in demand.

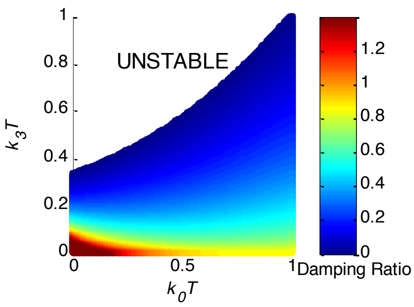

Fig. 3. Damping ratio with capacity adjustment gains k_0 and k_3

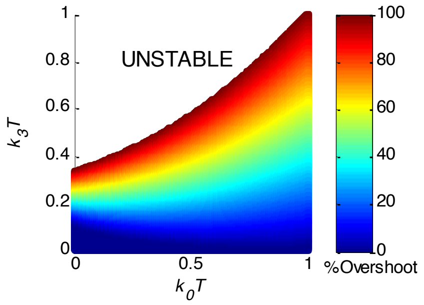

Fig. 4. Percent overshoot with capacity adjustment gains k_0 and k_3

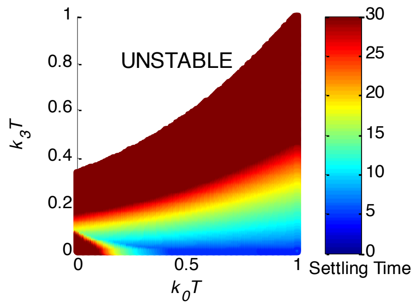

Fig. 5. Settling time [shifts] with capacity adjustment gains k_0 and k_3

5. Results

The coordinated capacity adjustment algorithm was evaluated using industrial work input data for a work system in a printed circuit board production factory. A time-scaled simulation model was implemented in Matlab that included the model in Fig. 1 and limits on per shift and per day capacity adjustments $\Delta c_0(t)$ and $\Delta c_3(t)$, respectively. The coordinated capacity adjustment algorithm summarized in Fig. 2 and the two dynamic performance goals described in Section 4 were used each shift to determine capacity adjustment gains k_0 and k_3. The industrial data included order arrival time and work content information for 2650 orders processed during 90 days with three shifts. The simulation model was used to predict behavior that would have resulted if the coordinated capacity adjustment algorithm had been employed in the work system if it was functioning according to Fig. 1.

The planned capacity was 6.5, 2.8 and 2.8 hours for the first, second and third shifts, respectively. The planned WIP was 10 hours; this prevented starvation of the work system (zero WIP) in the cases studied. Initial conditions were chosen to eliminate simulation startup transients.

Tables 1, 2 and 3 list statistical results obtained from the simulations with various capacity adjustment limits, the two dynamic performance goals (damping ratio ζ=1 and minimum $\|E\|_1$), and a third baseline performance case in which capacity adjustment gains were held constant at k_0=1 and k_3=0.25. These values represent a system without coordinated capacity adjustment, and they were chosen because gain combinations k_0=1, k_3=0 and k_0=0, k_3=0.25 produce dynamic response that is as rapid as possible without overshoot using only floaters and only overtime, respectively. Data for the last 60 days of the simulation were used in calculating the statistical results in all of the tables.

The results in Table 1 show that with unlimited capacity adjustments, both ζ=1 and minimum $||E||_1$ dynamic performance goals produced identical results. This is the case because all capacity adjustments are immediate, only use floaters, and hence the coordinated capacity adjustment algorithm always results in k_0=1, k_3=0. The baseline case k_0=1, k_3=0.25 is somewhat less optimal as indicated by $||E||_1$.

The results in Tables 2 and 3 show that when capacity limits were introduced, deviation from planned WIP increased. The minimum $||E||_1$ dynamic performance goal produced the best results as indicated by $||E||_1$, while both damping ratio ζ=1 and minimum $||E||_1$ were superior to the baseline case k_0=1, k_3=0.25. When the floater capacity limit was reduced from 2 hours/shift (Table 2) to 1 hour/shift (Table 3), the deviation from planned WIP increased significantly and, again, the minimum $||E||_1$ dynamic performance goal produced the best results as indicated by $||E||_1$. (Mean WIP was not used for performance comparison because the WIP regulation topology in Fig. 1 makes it strongly dependent on the chosen planned capacities.)

Tables 4, 5 and 6 show capacity adjustment results that correspond to the WIP results in Tables 1, 2 and 3, respectively. As expected, floater capacity adjustments decrease as the floater capacity adjustment limit is decreased. Correspondingly, overtime capacity adjustments increase as the portion of the WIP regulation burden that can be handled by floaters decreases.

6. Conclusions

It was shown that when multiple modes of capacity adjustments are available in a work system and adjustment in the various modes are limited in magnitude, coordination of these capacity adjustments can significantly improve work system dynamic behavior. A case study using industrial data was used to compare the behavior of three coordination schemes: fixed contributions (k_0=1, k_3=0.25); damping ratio ζ=1; and minimum sum of absolute error in response to a step change in demand (minimum $||E||_1$). The damping ratio ζ=1 dynamic performance goal required analysis of the discrete system characteristic equation to solve for capacity adjustment gains that resulted in ζ=1, while the minimum $||E||_1$ dynamic performance goal required searching for capacity adjustment gains that minimize the minimum sum of absolute error in step response. It was found in the case study that the minimum $||E||_1$ goal produced significantly better results when the magnitude of adjustments in the number of floaters in the work system was more limited. The damping ratio ζ=1 goal produced better results than the case with no coordination of capacity adjustments.

In the presence of capacity adjustment limits, WIP regulation was adapted to the present logistic situation. Coordination of capacity adjustments was accomplished using an algorithm in which floaters were adjusted first up to their limit. Then, with the floater capacity adjustment gain fixed at the value that produced the limit, the overtime capacity adjustment gain was found that met the desired performance goal (damping ratio ζ=1 or minimum $||E||_1$). In the case study, the overtime capacity adjustment gain was fixed at the beginning of each day, influencing the floater capacity adjustment gains for the second and third shifts. When the amount of available floater capacity adjustment was decreased, coordination of capacity adjustment modes became more important and the minimum $||E||_1$ dynamic performance goal produced better results.

The delays in and the times period between capacity adjustments were assumed to be constant in the work system that was studied. The WIP deviations can be expected to be greater for longer delays and longer adjustment periods. As these increase, the magnitudes of capacity adjustments generally must be decreased; for example, it can be seen in Figs. 3 and 4 that k_0 and k_3 must be decreased to obtain similar dynamic behavior as T is increased.

A single case study using industrial data was used in this paper to evaluate capacity adjustment mode coordination and two dynamic performance goals; one based on transfer function analysis (analysis of the characteristic equation) and one based on minimization of WIP deviation over time using iterative simulations. Additional studies with other dynamic performance goals (e.g., ζ≠1 or minimum sum of error squared in step response), a broader range of capacity adjustment limits, and larger statistical data sets would be expected to more completely characterize trends in WIP deviation and dynamic performance. Furthermore, other modes of capacity adjustment are available, and inclusion of these as well as consideration of their economic costs would be of significant interest in additional studies.

Table 1. Results [hours] without capacity limits

Performance goal	Mean WIP	Std. Dev. WIP	Minimum WIP	Maximum WIP	$\|\|E\|\|_1$
k_0=1, k_3=0.25	10.29	2.32	4.29	19.48	293
ζ=1	10.32	2.38	5.16	19.43	285
minimum $\|\|E\|\|_1$	10.32	2.38	5.16	19.43	285

Table 2. Results [hours] with floater capacity adjustment limit Δc_{0max}=2 and overtime capacity adjustment limit Δc_{3max}=3 [hours/shift]

Performance goal	Mean WIP	Std. Dev. WIP	Minimum WIP	Maximum WIP	$\|\|E\|\|_1$
k_0=1, k_3=0.25	10.7	3.45	3.67	22.34	445
ζ=1	11.05	3.17	4.86	22.28	419
minimum $\|\|E\|\|_1$	10.91	3.15	4.85	22.3	406

Table 3. Results [hours] with floater capacity adjustment limit Δc_{0max}=1 and overtime capacity adjustment limit Δc_{3max}=2 [hours/shift]

Performance goal	Mean WIP	Std. Dev. WIP	Minimum WIP	Maximum WIP	$\|\|E\|\|_1$
k_0=1, k_3=0.25	10.92	4.78	0.49	23.00	686
ζ=1	11.94	4.65	1.05	24.94	660
minimum $\|\|E\|\|_1$	11.65	4.40	1.29	24.45	606

Table 4. Results [hours/shift] without capacity limits

Performance goal	Mean $\|\Delta c_0\|$	Std. Dev. $\|\Delta c_0\|$	Mean $\|\Delta c_3\|$	Std. Dev. $\|\Delta c_3\|$
k_0=1, k_3=0.25	1.66	1.64	0.37	0.33
ζ=1	1.64	1.61	0	0
minimum $\|\|E\|\|_1$	1.64	1.61	0	0

Table 5. Results [hours/shift] with floater capacity adjustment limit Δc_{0max}=2 and overtime capacity adjustment limit Δc_{3max}=3 [hours/shift]

Performance goal	Mean $\|\Delta c_0\|$	Std. Dev. $\|\Delta c_0\|$	Mean $\|\Delta c_3\|$	Std. Dev. $\|\Delta c_3\|$
k_0=1, k_3=0.25	1.39	0.72	0.56	0.51
ζ=1	1.26	0.73	0.0031	0.013
minimum $\|\|E\|\|_1$	0.87	0.7	0.017	0.063

Table 6. Results [hours/shift] with floater capacity adjustment limit Δc_{0max}=1 and overtime capacity adjustment limit Δc_{3max}=2 [hours/shift]

Performance goal	Mean $\|\Delta c_0\|$	Std. Dev. $\|\Delta c_0\|$	Mean $\|\Delta c_3\|$	Std. Dev. $\|\Delta c_3\|$
k_0=1, k_3=0.25	0.94	0.19	0.94	0.59
ζ=1	0.81	0.3	0.073	0.13
minimum $\|\|E\|\|_1$	0.87	0.29	0.16	0.25

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