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Lean Production Control at a High-Variety, Low-Volume Parts Manufacturer

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Eaton Electric General Supplies, a parts manufacturing unit that supplies parts for Eaton's electrical business unit, implemented several lean control elements in its high-variety, low-volume production units. These control elements include a constant work-in-process mechanism to limit and control the amount of work in process, first-in-first-out sequencing to control the order of departing jobs, and takt time to control the timing of departing jobs. We conducted a simulation study to (1) illustrate the control-element operations for planners and supervisors, (2) indicate the general applicability of the elements, and (3) support the development of a production progress screen to support the workers in the production units.

Key words: CONWIP; FIFO; takt time; high-variety, low-volume; simulation.
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Empirical studies show that both small and large manufacturers have significantly improved performance by implementing lean manufacturing principles (White et al. 1999). The lean approach provides firms with a framework and a set of principles to identify and eliminate unnecessary sources of variability and to improve the performance of their production systems (Hopp and Spearman 2004). As a result, many companies are interested in implementing lean control principles, such as *pull* and *takt time control*. The key to the effectiveness of pull systems is that they explicitly limit the amount of work in process (WIP) that can be in a system (Hopp and Spearman 2004). Takt time control is a concept predominantly used in final assembly production to efficiently allocate production throughout a factory (Linck and Cochran 1999, Miltenburg 2001). Takt time sets a fixed production pace, which is equal to the customer's rate of demand. It can be computed by dividing the available production time by the customer demand (i.e., current backlog of orders). The constraints imposed by these lean manufacturing principles simplify the control of the production system and provide motivation to reduce the variability in the production system.

Pull and takt time lean control principles have mainly been applied in high-volume flow environments in which jobs move through the production system in one direction along a limited number of identifiable routings. This paper, however, addresses the implementation of elements of lean control for a typical make-to-order (MTO) job shop that manufactures many part types in small batches. Our initial focus was on a relatively independent production unit at Eaton Electric General Supplies (EEGS), the Copper Bars production unit (CB unit). EEGS, an internal supplier of Eaton's electrical business unit in Hengelo, The Netherlands, supports Eaton's Holec brand. Eaton's electrical business unit develops, produces, and sells electrical power distribution and control equipment for industrial, commercial, and residential markets. EEGS comprises three independent production units based on the product characteristics: sheet metal, turning and milling, and copper bars.

Prior to June 2007, the CB unit was experiencing large amounts of WIP, and its job waiting times varied widely. Employees did not clearly understand which job they should select to work on next; they often chose to remain at their preferred machines although 20 percent of the jobs were flagged as rush orders. This resulted in unreliable and uncertain lead times. The EEGS management was eager to resolve these problems, preferably by using lean manufacturing principles. EEGS's American parent company strongly supports the "lean philosophy," encourages its firms to implement lean approaches, and uses lean implementation as a measurement criterion. Management thus desired to create a stable and efficient production system for its CB unit in which predictable and short throughput times would be realized by using elements of lean control.

As a partner in the Lean Operations Research Center (LO-RC, http://www.rug.nl/feb/lo-rc), EEGS sought support from researchers and master students at the University of Groningen. In cooperation with EEGS management, we distinguished three appropriate elements of lean control for the CB unit—constant WIP (CONWIP), first-in-first-out (FIFO) sequencing, and takt time—and combined these in a lean control system. CONWIP serves to limit the number of jobs in the CB unit. This supports the goal of short average throughput time for jobs in the unit. FIFO requires that workers in the CB unit focus on the oldest jobs in the system, thus reducing the variability in throughput times. Takt time encourages the workers to realize a regular flow of jobs through the system in line with customer demand. By introducing takt time, the lead times of jobs become fixed (i.e., CONWIP level × takt time). Slomp et al. (2009) describe the CB unit in detail and discuss how the lean control system is integrated into the EEGS planning and control system.

Convincing the project's stakeholders (i.e., the operators, supervisors, and planners) that the suggested lean control system would work in the CB unit's high-variety, low-volume environment was a challenge. Some stakeholders did not fully understand the underlying principles of lean; in addition, some supervisors and planners were skeptical of the proposed system. Given these attitudes, we developed a "game," partly based on computer animation, to give these stakeholders insights into the basic workings of the control system. We developed a simulation study to show the general applicability of the lean control system and proved that even if the processing times varied substantially, the production control system would still perform well. The simulation study's output convinced EEGS management to proceed with implementing the control system in all its production units. The simulation study also supported the design of a production progress screen, which is currently implemented in three production units, to support the production units in realizing their targets. An evaluation of the CONWIP/FIFO/TAKT lean control system, as it functioned in practice for more than a year in the CB unit, shows that the unit substantially improved its performance.

Characteristics of the CB Unit

At the CB unit, copper strips undergo operations that include punching, trimming, bending, drilling, milling, and bench-working. The production process starts with punching. Jobs that require the same thickness of copper bar are grouped together and punched as one job, sometimes from a single copper bar, to reduce copper waste and set-up times. The operations that follow punching are grouped under the heading "strip manufacturing." The processes that encompass strip manufacturing entail a large variety of job routing. An analysis of approximately 3,500 jobs showed that each involved between one and five processing steps, with an average of 1.6. The average processing time per operation was approximately 32 minutes, but with large differences between operations on the various machines and substantial processing variability on each machine. The CB unit operates on a two eight-hour shift pattern (a morning shift and an evening shift). Despite this pattern, three employees work only in the daytime because of health reasons; thus, they work during part of both shifts. Depending on the time of the day, between five and nine workers are available for production activities. Because more machines than workers are available, the CB unit can be characterized as a "dual-resource-constrained" job shop.

The production control mechanism used in the CB unit before the implementation of the lean control system can be characterized as "push" because it did not explicitly limit the amount of WIP released to the shop floor. On the shop floor, the CB unit tried to meet the promised lead times using a priority system that was meant to control the throughput times of jobs. The priority given to jobs ranged from rush orders (highest priority) to normal orders (lowest priority). If a job was behind schedule, a planner increased its priority until it was back on schedule. This meant that jobs were continually sped up or slowed down to satisfy customers' timing demands. The CB unit's customers expect fast, on-time deliveries of high-quality products at a low cost. Therefore, reducing lead time (speed) and improving the service level (reliability) are of major importance. The proposed CONWIP/FIFO/TAKT system's objective was to improve the control situation on the work floor.

Getting the Message Across

To gain acceptance of the CONWIP/FIFO/TAKT system by operators, supervisors, and planners, we developed a gaming and animation tool using UGS Corporation's object-oriented simulation software package, Tecnomatix Plant Simulation 7.6. Figure 1 shows a screen capture from the animation. We used this animation to present the status on the shop floor over a given period. We used constructions made of Lego bricks to represent raw material, semifinished jobs, and finished jobs, and we developed processing information sheets to indicate the tasks at each workstation.

We organized a session with supervisors and planners to play the game. Our objective was to give them insights into how the lean control system works and to convince them that the system would work in the CB unit's high-variety, low-volume environment. The animation used production data of typical jobs (routing and processing-time information), which we demonstrated on a large screen. We showed the machines, the workers, the jobs, and the time progression (see Figure 1). We allowed each session attendee to play the game and associated each with a worker in the animation. After finishing an operation on a job, the players had to decide which job to work on next to ensure the on-time delivery of all the jobs. The animation used the players' decisions as inputs and returned timing information to them. We physically represented the jobs using Lego brick constructions and required players to read the instructions and process the jobs accordingly. If the takt time was exceeded, we examined the causes (such as a worker continuing to process jobs at his (her) machine rather than moving to an older job on another machine) and discussed possible solutions.

Playing the animation game had a very positive effect on the acceptance of the CONWIP/FIFO/TAKT system by the EEGS supervisors and planners. They clearly saw the potential for improvement by implementing the lean control elements. The expected benefits included a better understanding of operations on the work floor, reduced variance in throughput because workers would prioritize those jobs that had been in the system for the longest time, reduced time by workers searching for their next task, and

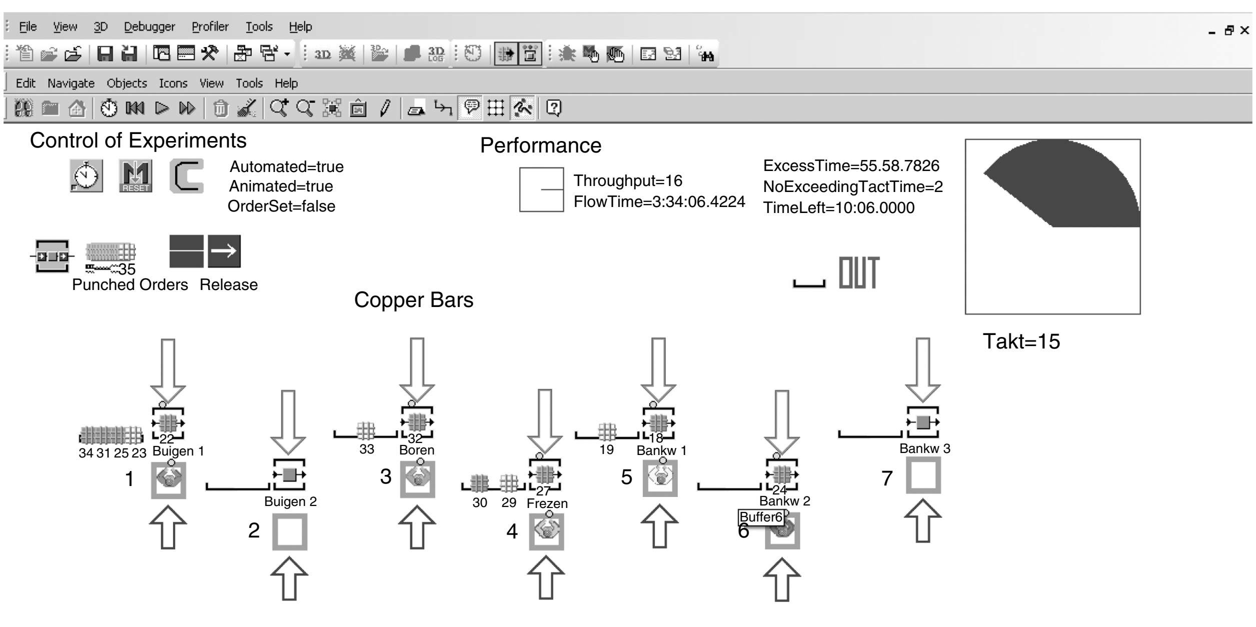

Figure 1: In this diagram, we show a screen capture of the animated simulation.

improved worker motivation. These benefits would lead to a more stable production system in which predictable (i.e., fixed) and short throughput times could be realized. Initially, we used the game with supervisors and planners only. When management suggested that we also introduce it to the shop floor workers, we recommended a stepwise implementation plan in which we would gradually introduce them to the new system. Although management agreed with this approach, it decided that we should only introduce the game to the workers if they required training; ultimately, such training was not considered necessary.

Simulating the Lean Production Control Elements

Although supervisors and planners embraced the CONWIP/FIFO/TAKT system, we decided to simulate it in more detail. Each element in the control system imposes additional constraints on the operation of the production unit and affects system performance. Simulation is useful to illustrate these effects. We were further motivated to do a simulation study by a planner's comments that the large variety of job sizes (i.e., processing times) could be problematic in implementing the new control system. Therefore, in our simulation study, we specifically showed how processing variability, which can be seen as a major characteristic of a high-variety, low-volume environment, can have an impact on performance when implementing each control element. We decided to simulate a small, hypothetical production system to avoid unnecessary discussions about the details of any particular production unit.

The simulated production system consisted of seven machines and five workers, each of whom was able to operate all machines with equal proficiency. We modeled job shop routing for jobs by randomly assigning a sequenced list of machines (ranging from 1 to 7) to each job, and set 4 as the average number of machines that needed to operate on a specific job. Because we set the average processing time at 32 minutes per operation, the work content of an average job was 128 minutes (4×32).

We assumed that once a specific machine worked on a job, the job would not return to that machine. We also assumed no machine failures, no absenteeism, and sufficient jobs available to enter the system when required.

The "where rule," which assigns a worker eligible for transfer to a machine, is based on a first-in-system, first-served (FISFS) approach—a worker goes to the available machine with the oldest job in its queue and processes that job. A worker who finishes a job is again available for transfer; this represents a so-called "central when rule." By contrast, it is common industry practice for a worker to remain working at a machine until the queue of jobs at that machine becomes empty; this is often referred to as a "decentral when rule." The central when rule results in lower throughput times than the decentral when rule.

We distinguished three control modes in our simulation study: CONWIP, CONWIP/FIFO, and CONWIP/FIFO/TAKT. In the CONWIP mode, we simulated the production system with a constant WIP level, i.e., the CONWIP level. Finishing a job in the system thus initiates the release of a new job to the system. In the CONWIP/FIFO mode, a new job is released only when the oldest job in the system completes. If jobs complete ahead of the FIFO sequence, they remain in the system and no new jobs are released until the oldest job has finished, thus decreasing the real WIP, which we define as the number of jobs in the production system that still need (some) processing. As such, workers will at times have fewer jobs available for processing. The CONWIP/FIFO/TAKT mode adds an additional constraint that a job will only be released at a takt moment—a moment in time with intervals of at least the minimum possible takt time. Assuming 100 percent worker utilization, the minimum possible takt time equals 25.6 minutes (128/5—the total work content of an average job divided by the number of workers in the system). If the oldest job in the production system is finished at a takt moment, it leaves the system and a new job is released. If the next oldest job is not finished within the takt time, the next takt moment will be delayed until the job has been finished. At that moment, the job leaves the system and a new job is released; the next takt moment at which another new job can be released is set 25.6 minutes later.

In our simulation study, we also explored the impact of processing-time variability on performance when using the different control modes. As we mentioned above, several employees were concerned about the effect of processing variability on the applicability of the control system. We used a gamma distribution, which is a two-parameter continuous probability distribution with a scale parameter beta and a shape parameter alpha, to determine processing times. The level of variability can easily be changed by altering the parameters of the gamma distribution. We distinguished two levels of processing-time variability. The first level represents low variability (Low) with alpha 8 and beta 4, which equals an 8-Erlang distribution with a squared coefficient of variation (SCV) of 0.125. The second level represents high variability (High), with alpha 1 and beta 32, which equals an exponential distribution with a SCV of 1. For both variability levels, the average processing time per operation equals 32 minutes (alpha × beta), which is equal to the average in the empirical data set for the CB unit.

Before explaining the performance indicators used in our simulation study, we will first define some important times during a job's stay in the production unit. Job release (t_r) indicates the time that a job enters the production system and that operators are allowed to start working on the first operation that the job must undergo. Job start time (t_s) is the time that the first operation actually starts. Job finishing time (t_f) indicates the time that the job finishes its last operation. Job departure time (t_d) is the time that the job leaves the production system, thus triggering the release of a new job. In the CONWIP/FIFO/TAKT mode, jobs ideally leave the production system after a fixed lead time (FLT) equal to CONWIP level × takt time; t_d then equals $t_r + \text{FLT}$.

In our simulation study, we measure the system performance by using the delivery performance (DEL), the worker utilization (UTIL), and the average status of a job in the system (S1, S2, S3) expressed as a percentage of FLT. DEL is measured as the percentage of jobs that stays in the system no longer than the FLT (i.e., $t_f - t_r \leq \text{FLT}$). The production unit is responsible for ensuring that jobs spend less than the FLT in the production system. UTIL is measured as the percentage of time that a worker is busy working on jobs; it is a measure of efficiency. The status of a job in the production system can be S1, S2, or S3:

(1) S1: the job has not yet started (S1 is calculated as $(t_s - t_r)/\text{FLT}$);

(2) S2: the job is in the process (S2 is calculated as $(t_f - t_s)/\text{FLT}$); or

(3) S3: the job has finished but cannot formally leave the system because of constraints in the control modes (S3 is calculated as $(t_d - t_f)/\text{FLT}$).

S1, S2, and S3 are important performance indicators because they show the extent to which the production unit has some slack that it can use to achieve the required performance.

The CONWIP level is likely to be an important moderating factor because inventory stock is able to absorb fluctuations in the workload of workers. However, the CONWIP level must be as low as possible. It is related directly to the throughput times of jobs and to other advantages associated with the control principles, such as the extent of the overview of work floor activities and the time needed to find appropriate jobs. The CONWIP levels in our simulation study ranged from 10 to 60 jobs.

All the simulation models were written in UGS Corporation's object-oriented discrete event simulation software package, Tecnomatix Plant Simulation 7.6. Our models are stochastic, steady state, and nonterminating. We used multiple (40) replications, each with the same initial conditions, to estimate the steady-state means of the output parameters (Robinson 2004). We used different seeds for each replication to maximize sampling independence. We set the run length at 6,640 hours, which is roughly equivalent to a two-year working period for a system operating two shifts. In the next section, we discuss our results.

Insights Provided by the Simulation Study

Figures 2, 3, and 4 present the major outcomes from our simulation study. Note that a CONWIP level of 25 or greater will achieve a worker utilization of almost 100 percent when using the CONWIP mode, even when a large variability in processing time exists. This result strengthened our initial view that the WIP level in the CB unit could be reduced substantially without reducing the efficiency of the unit. Figure 2 also shows that a high delivery performance, as we define in our study, cannot be achieved using a CONWIP control

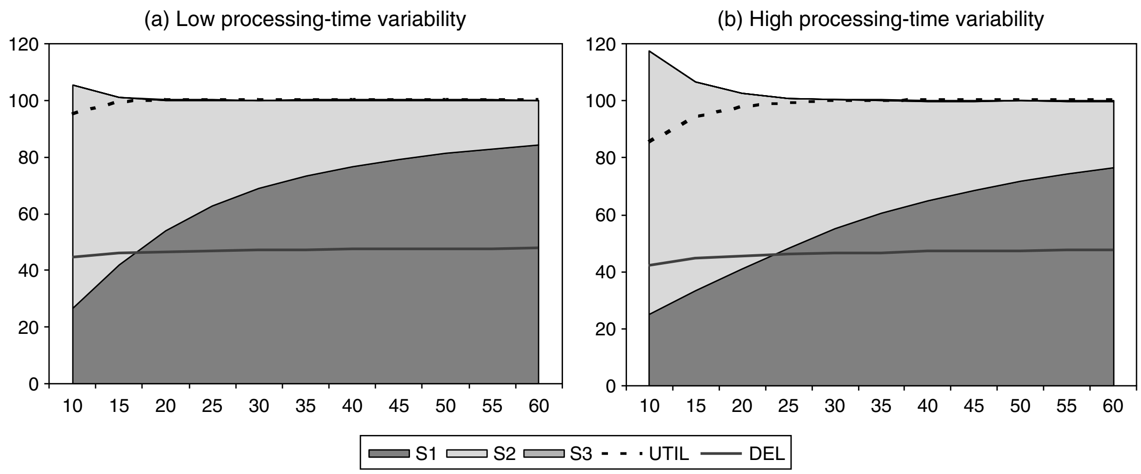

Figure 2: In these graphs, we show performance results using the CONWIP mode. We plot the CONWIP level along the x-axis. The y-axis represents the percentage of jobs with $t_f - t_r \leq$ FLT for DEL, the worker utilization percentage for UTIL, and the average status of a job in the system expressed as a percentage of FLT for S1, S2, and S3.

mode. However, the CONWIP mode does have a simple release mechanism, which is attractive in a production environment—when a job completes, another job will be released to the production system. This approach can be adopted by simply creating a rule requiring that a card linked to a finished job must be connected to a new job before the job is released. As our simulation study shows, this mechanism does not ensure reliable (i.e., $t_f - t_r \leq \text{FLT}$) delivery of jobs from the production unit. Increasing the CONWIP level only leads to longer slack times (S1) before the production of a job starts.

Figure 3 shows how the CONWIP/FIFO control mode impacts the performance of the production system. In the CONWIP/FIFO mode, finished jobs cannot leave the system if older jobs are still in the system. Unlike with the CONWIP mode, jobs can also have an S3 status, thus reducing the real WIP. Note

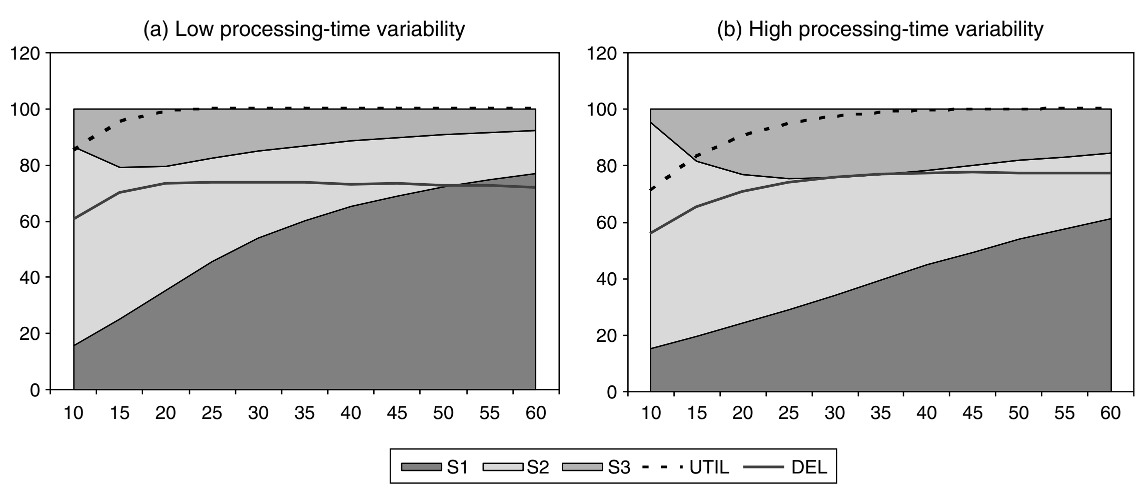

Figure 3: In these graphs, we show performance results using the CONWIP/FIFO mode; we plot the x-axis and y-axis as represented in Figure 2.

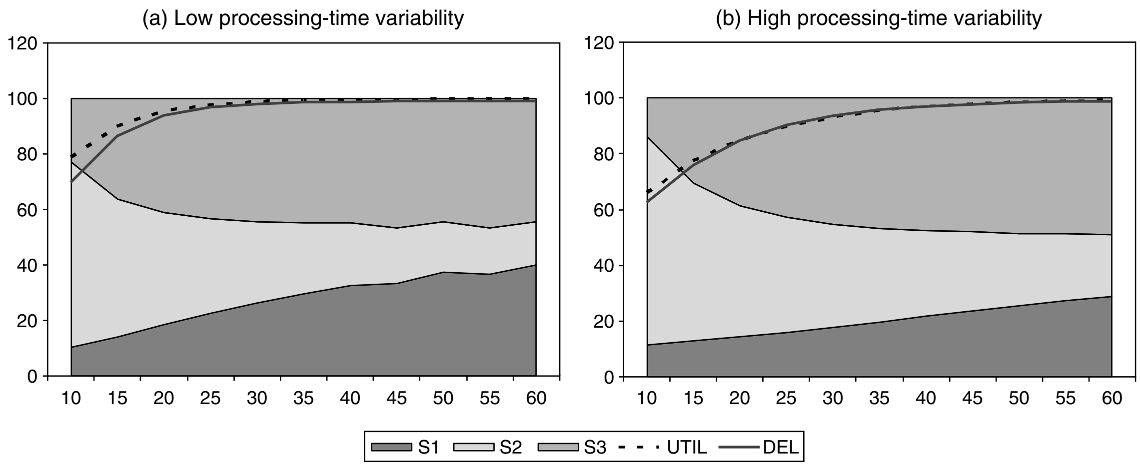

Figure 4: In these graphs, we show performance results using the CONWIP/FIFO/TAKT mode; we plot the x-axis and y-axis as represented in Figure 2.

that applying the CONWIP/FIFO mode improves the delivery performance to a maximum level that is still substantially below 100 percent. This shows that focusing on the oldest jobs while having a constant number of jobs in the system (i.e., the CONWIP level) is not an adequate approach if one wants to achieve reliable job delivery from the production unit (i.e., $t_f - t_r \leq$ FLT). The effect of the variability in processing time is also intriguing. Not surprisingly, a higher variability has a somewhat negative impact on the workforce utilization. A CONWIP level of more that 40 (i.e., eight times the number of workers) is needed to achieve a near-100 percent worker utilization. A high variability, provided it is combined with relatively high CONWIP levels, does not have negative consequences for the system's performance compared with that of a system with low processing-time variability. We can explain this seemingly contradictory finding by realizing that the real WIP (jobs with either status S1 or S2 available to the workforce) is less with high variability because of the increased complexity in conforming to the FIFO rule. The resulting lower level of available WIP is responsible for the improved performance (i.e., $t_f - t_r \leq$ FLT).

Figure 4 presents simulation results using the CONWIP/FIFO/TAKT mode. This mode leads to a high workforce utilization and high delivery performance when a reasonable CONWIP level is set. This finding suggests that if the workforce focuses on realizing FIFO sequencing and the required production speed (i.e., takt times), this can be sufficient to achieve an efficient, controllable production unit. Note that, in this mode, the real WIP (i.e., jobs with either status S1 or S2) available to the workforce is approximately 50 to 60 percent of the CONWIP level. Greater variability in processing time requires higher levels of CONWIP to realize the same performance (UTIL and DEL) as in the case of low processing variability.

Implementation and Impact

As noted earlier, we implemented the CONWIP/FIFO/TAKT system in a stepwise manner using the three simulated control modes as reference. First, we gradually reduced the number of jobs, which was initially approximately 150, in the CB unit. Each job now is assigned a card with a unique number. When a job completes, the card is available for a new job. Workers were encouraged not to start working on new jobs but to proceed with jobs currently in the system. Free cards, which were not used for new jobs, showed possibilities for reducing WIP. Based on practical experience over time, we decided to keep 60 cards in the system (i.e., the CONWIP level). This significant reduction in the maximum number of jobs on the work floor gave workers in the CB unit a better overview of what needed to be done and also sufficient opportunities to work continuously. This

Production progress screen

Day	Wed	Start	06:00 AM	Finished products	26
Takt time (min)	18	Stop	11:00 PM	To be produced	34
Daily production	60	Time	10:33 AM	Lead/backlog	11

Nr.	Order	Time	Nr.	Order	Time	Nr.	Order	Time	Nr.	Order	Time
41	**688390**	**23:34**	54	687872	03:50	19	0	00:00	38	0	00:00
17	688140	16:36	16	688238	02:58	20	0	00:00	40	0	00:00
47	688131	15:47	3	688202	01:34	21	0	00:00	43	0	00:00
11	688184	13:17	1	0	00:00	22	0	00:00	45	0	00:00
44	688221	11:50	2	0	00:00	23	0	00:00	48	0	00:00
46	688239	10:46	4	0	00:00	24	0	00:00	49	0	00:00
29	687899	10:38	5	0	00:00	25	0	00:00	51	0	00:00
10	687873	10:34	7	0	00:00	28	0	00:00	52	0	00:00
39	688237	08:54	8	0	00:00	30	0	00:00	53	0	00:00
34	687874	08:39	9	0	00:00	31	0	00:00	55	0	00:00
50	687900	08:33	12	0	00:00	32	0	00:00	56	0	00:00
6	688405	06:34	13	0	00:00	33	0	00:00	57	0	00:00
26	688402	06:03	14	0	00:00	35	0	00:00	58	0	00:00
27	688395	04:26	15	0	00:00	36	0	00:00	59	0	00:00
42	688387	04:10	18	0	00:00	37	0	00:00	60	0	00:00

Figure 5: In this screenshot, we show a production progress screen.

CONWIP level is approximately eight times the number of workers typically in the system.

To support the FIFO and TAKT elements in the lean control system, we developed a "production progress screen" (see Figure 5). This screenshot shows data at the CB unit as of Wednesday, July 15, 2009, at 10:33 AM. Workers enter a job into the computer when they start to work on it (t_s) and associate it with a free card ("Nr." on the screen). This means that, in the system as implemented, $t_r = t_s$. The screen shows all the numbers and cards linked to jobs and the length of time that the jobs have been in the system ("Time" on the screen is the current time minus t_r). After the final operation on a job completes (t_f), the worker enters this information and the job is removed from the screen. The associated card is then available for a new job. The screen indicates late jobs (i.e., jobs longer than FLT in the system) by highlighting them in red. Because the flow-time calculation in the implemented system only starts when the first operation on a job commences, jobs will have more slack before being deemed late (i.e., turning red) than in the simulation in which the flow time includes the waiting time between the release of a job and the start time of a job (i.e., jobs with an S1 status). In Figure 5, the first job (order 688390, card 41) has been in the system too long; therefore, the system marks it in red (note that we indicate this lateness by bolding the order information). Operators were encouraged to work on the oldest jobs to achieve good performance with respect to the time that jobs were in the system (i.e., DEL in our simulation study). To encourage the workers to focus on FIFO, we asked them to give reasons for each late order; they identified 10 possible reasons. The worker who carries out the final operation on a late job must indicate the primary reason for the lateness, sometimes after a short discussion with other workers, by simply clicking on 1 of the 10 predefined reasons.

The screen also indicates the takt time (18 minutes in this example), which equals the available time divided by the number of orders to be produced. This means that, on average, a job should complete every 18 minutes and a new job should start its initial operation every 18 minutes. By comparing the number of jobs completed prior to the current time on a particular day ("Finished products" at 10:33 AM) with the number of jobs that should have completed (calculated from the takt time), we can determine the lead or backlog ("lead/backlog" on the screen), which is 11 jobs in Figure 5 (note that a negative sign indicates a backlog). The lead/backlog indicator gives workers an insight into their productivity. A large backlog needs careful interpretation; it is not necessarily a negative indicator. In this unit, because more workers are available as the day progresses, a backlog early in the day is to be expected.

The workers, the supervisor, and the logistics manager have a good insight into what an acceptable backlog is at the starting time of the day-shift workers. By monitoring their progress on the production progress screen, workers are motivated to achieve the required daily production.

The production progress screen shows all the elements of the CONWIP/FIFO/TAKT lean control system. The screen (1) identifies the number of cards in the system (60, the CONWIP level), (2) shows the required sequence in which the workers should finish the operations, and (3) draws attention to the responsibility of workers to deliver the jobs on time by avoiding or limiting the number of late jobs (i.e., highlighted in red). However, some differences exist between the implemented and the simulated control systems. In the implemented system, worker nonproductivity is avoided wherever possible. Even if some jobs are already late, workers will start working on new jobs if other job options are not available. The release of jobs is also triggered in a different way. In the implemented system, workers enter a job into the computer when they start working on it, provided that a free card is available. Also, the way that workers use the takt time information differs from that simulated in the CONWIP/FIFO/TAKT mode. In reality, the workers focus on the lead/backlog information. In doing so, they attempt to deliver output according to their takt times. These differences from the simulated system were included in the implementation of the CB unit's lean control system because of practical considerations.

The production progress screen in Figure 5 shows that, in line with our simulations, the WIP in the system (related to S2 in our simulation) is substantially lower than the CONWIP level. Simulation indicated the need for this lower WIP level. EEGS currently sets no clear limits for the minimum WIP level allowed in the system, and no such limit is required. The CB unit workers know that (1) if the WIP level is too low, some workers may not have enough work, and (2) if the WIP level is too high, then a high delivery performance (i.e., a low number of red orders) becomes impossible.

Workers and supervisors were very enthusiastic about using the screen because it helped them to prioritize jobs and to have up-to-date information about production performance. As a result of implementing the lean control elements, the throughput time in the CB unit has fallen from approximately 4.2 days to 1 day. Workers and supervisors enjoy this new situation and note several advantages, such as a better overview of the situation and less time spent looking for the urgent jobs. The EEGS planner uses the takt information (number of jobs per day) to load the CB unit and to decide whether outsourcing is required (Slomp et al. 2009). Because of the improved controllability of the CB unit, the on-time-to-request performance (OTR) of jobs initially assigned to the CB unit by the firm's enterprise resource planning (ERP) system has improved from approximately 50 percent in 2005–2007 to 61 percent in 2008. The production progress screen was implemented at the beginning of 2008. We note that several factors that we do not discuss in this paper are also considerations in the low OTR delivery performance. Nevertheless, the EEGS logistics manager believes that the OTR improvement comes mainly from the improved controllability of the CB unit. Furthermore, the workers and the supervisors tell us that they feel that the new control system has aided worker productivity. Other factors that affected worker productivity include technical improvements and a reduction in the use of temporary workers because of reduced demand.

As we note above, the workers must give a reason if a job completes late. In 2008, about 20 percent of jobs completed late; the main reasons given were insufficient attention (36 percent), limited worker flexibility (28 percent), and technical problems (28 percent). Long job-processing times were only mentioned as the reason for poor delivery performance in 1 percent of all cases. These outcomes have convinced EEGS management to invest in the cross-training of workers at the CB unit, to intensify the maintenance of some machines, and to motivate and teach workers to prioritize the right jobs. This proves that introducing the new lean control system, i.e., the production progress screen, also supports continuous improvement, a main element of lean thinking.

Based on the success of the production progress screen at the CB unit, EEGS management decided to implement the lean control system in its other production units. In September 2008, the system was also successfully running in the turning/milling unit. Currently, EEGS is implementing it in the sheet metal unit. This will be a slightly different implementation because of this unit's flow characteristics. However, management strongly believes that the lean production control system is robust and can be used in many manufacturing environments.

Conclusions

In this paper, we have shown how elements of lean control systems can be used in high-variety, low-volume production units. These control elements include the CONWIP mechanism to limit and control the amount of WIP, FIFO sequencing to control the order of departing jobs, and takt time to control the timing of departing jobs. These lean control elements have been integrated into a CONWIP/FIFO/TAKT system that EEGS, the parts manufacturing unit supporting Eaton's Holec brand in Hengelo, The Netherlands, implemented in several of its production units.

The development of the CONWIP/FIFO/TAKT system was supported by a simulation process. We used gaming and animation to illustrate the system's feasibility. This activity contributed to the system's acceptance by EEGS management. We then performed a simulation study to prove that implementing lean elements could lead to good performance in high-variety, low-volume production units. The study showed that the workforce in a production unit must focus on the number of active jobs in the system (related to S2 in the simulation), the FIFO sequence, and the required output of the system calculated using takt times. We incorporated these insights in a practical application using the production progress screen, which EEGS still uses.

The evaluation of the CONWIP/FIFO/TAKT system at EEGS indicates the success of such a system in high-variety, low-volume environments. Therefore, it seems likely that such a system can be successfully applied in many industrial situations.

References

Hopp, W. J., M. L. Spearman. 2004. To pull or not to pull: What is the question? *Manufacturing Service Oper. Management* **6**(2) 133–148.

Linck, J., D. S. Cochran. 1999. The importance of takt time in manufacturing system design. *Proc. 1999 SAE Internat. Automotive Manufacturing Conf.* (*IAM99-34*), *Detroit*.

Miltenburg, J. 2001. One-piece flow manufacturing on U-shaped production lines: A tutorial. *IIE Trans.* **33**(4) 303–321.

Robinson, S. 2004. *Simulation: The Practice of Model Development and Use*. John Wiley & Sons, Chichester, UK.

Slomp J., J. A. C. Bokhorst, R. Germs. 2009. A lean production control system for high-variety/low-volume environments: A case study implementation. *Production Planning Control* **20**(7) 586–595.

White, R. E., J. N. Pearson, J. R. Wilson. 1999. JIT manufacturing: A survey of implementations in small and large U.S. manufacturers. *Management Sci.* **45**(1) 1–15.

Han Busschers, Logistic Manager EEGS, Eaton Electric B.V., Europalaan 202, 7559 AA Hengelo, The Netherlands, writes: "The paper of Dr. Jos Bokhorst and Professor Dr. Ir. Jannes Slomp gives an adequate view of the development and introduction of Lean Production Control in the three production units of EEGS. In all three units, we now satisfactorily apply a Production Progress Screen, forcing the team members of the unit to apply the CONWIP, FIFO, and TAKT Concept. As mentioned in the paper, the throughput times in the production units have been reduced substantially. The data and the qualitative comments made in the paper are correct. The new lean control system has improved the controllability of the units, enabling our planning department to make more adequate decisions with respect to the loading of the cells.

"The animation and simulation study performed by Jos Bokhorst and Jannes Slomp were important for us to gain understanding of the system and to learn its basic principles. The simulation study also supported us to decide for the parameters within the Production Progress Screen. We hope to apply the simulation also for introducing lean production control principles in other parts of our company."