Analysis of a closed flow production system with a dynamic WIP level

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Challenges & Goals of Industrial Planners

Challenges

- Stochastic processing times
- Configuration of system-specific input parameters
- Complex real-life production systems

Goals

- Optimization of throughput and WIP
- Robustness
- Low investment costs

Closed Flow Production System with a constant WIP Level

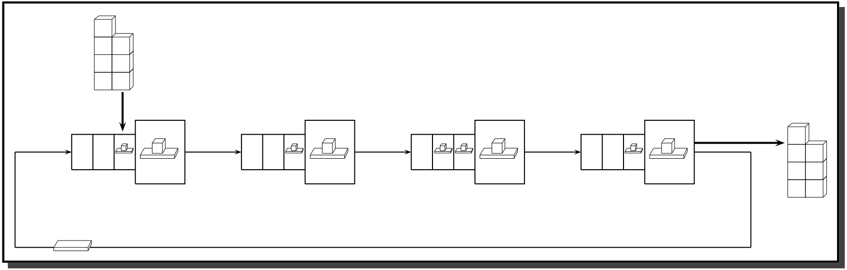

Figure 1: Closed flow production system

- Finite buffers
- Random processing times
- Constant number of pallets (constant WIP)

Closed Flow Production System with a dynamic WIP Level

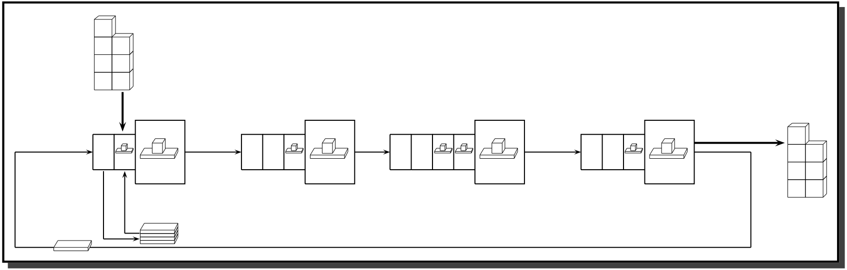

Figure 2: Closed flow production system with a dynamic WIP level

- Maximum number of pallets (dynamic WIP)
- Full buffers behind last station ⇒ remove pallets
- Empty buffers behind last station ⇒ add pallets

Closed Flow Production System with a Dynamic WIP Level

System characteristics

- Pallets are removed when the buffer capacity behind the last station is exhausted
- Pallet number is increased when there is sufficient capacity left

System effects

- No blocking of the last station and starving of the first station
- Average WIP is below the maximum number of pallets

Related Literature

Evaluation of closed flow production systems with a constant WIP

- Bouhchouch, A., Y. Frein, Y. Dallery (1996) *Performance evaluation of closed tandem queueing networks with finite buffers*.
- Lagershausen, S., M. Manitz, H. Tempelmeier (2013) *Performance analysis of closed-loop assembly lines with general processing times and finite buffer spaces*.

Dynamic card adjustment in Conwip and Kanban systems

- Hopp, W.J., M.L. Roof (1998) *Setting WIP levels with statistical throughput control (STC) in CONWIP production lines*.
- Framinan, J.M., P.L. González, R. Ruiz-Usano (2006) *Dynamic card controlling in a Conwip system*.

Related Literature

Control policies

- Liberopoulos, G., Y. Dallery (2000) *A unified framework for pull control mechanisms in multi-stage manufacturing systems*.
- Gershwin, S.B.(2000) *Design and operation of manufacturing systems: the control-point policy*.
- Grosfeld-Nir, A., M. Magazine (2002) *Gated MaxWip: A strategy for controlling multistage production systems*.
- Gebennini, E., A. Grassi, C. Fantuzzi, S.B. Gershwin, I.C. Schick (2013) *Discrete time model for two-machine one-buffer transfer lines with restart policy*.

Simulation Study

Simulation framework

- 2 industrial examples, 2 theoretical examples
- Random processing times following a gamma-distribution
- Replication length: 101000 h, warmup: 1000 h

Simulation goal

- Comparison of closed flow production systems with constant and dynamic WIP

⇒ Throughput, system state probabilities and average WIP

⇒ Optimal buffer allocation

Simulation Results

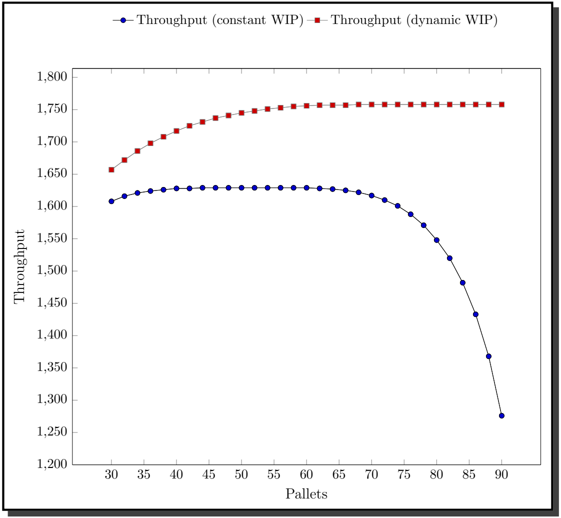

Figure 3: Throughput of a system with 9 manual working stations, CV=0.8

Simulation Results

Closed flow production system with a constant WIP

- Throughput rises with an increasing number of pallets until the optimum
- Throughput decreases with a further increase of the pallets
- Average WIP equals the number of pallets

Closed flow production system with a dynamic WIP

- Throughput rises with an increasing number of pallets and converges on the throughput of an open flow production system
- Average WIP is below the number of pallets

Simulation Results

Throughput improvement - Industrial examples

	Δ Throughput		
Example	CV=0.5	CV=0.8	CV=1
Example 1 (9 stations)	3.95%	7.88%	9.77%
Example 2 (7 stations)	0.45%	2.61%	4.36 %

⇒ Impact of the dynamic WIP grows with the system variability

Throughput improvement - Theoretical examples

Example [a]	Δ Throughput
BFD96Ex2b	1.54%
BFD96Ex2c	0.87%
BFD96Ex2d	0.49%

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[a] Bouhchouch et al. (1996)

Simulation Results

Buffer allocation

- Constant WIP: optimal buffer allocation dependent on pallet number
- Dynamic WIP: optimal buffer allocation independent of pallet number
- Pattern of buffer allocation with dynamic WIP: buffer between first and last station is chosen as small as possible

Evaluation Approach

Approximation

- Grounds on Lagershausen, Manitz and Tempelmeier (2013)
- Modification of $\mu_d(M-1,M), \zeta_d(M-1,M)$

⇒ Avoidance of blocking effects of the last station

Flowchart

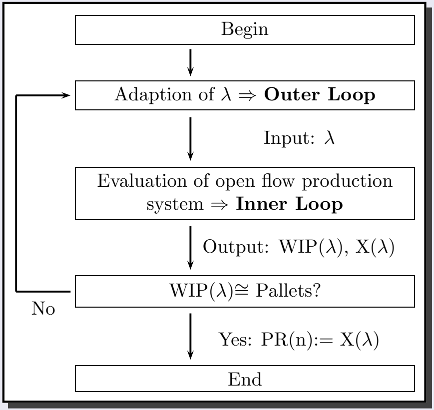


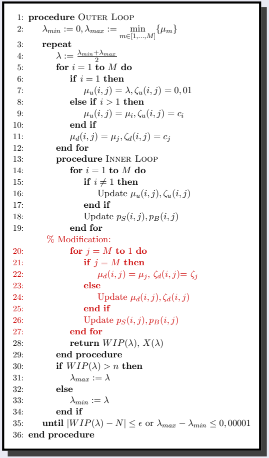
Figure 4: Flowchart of the approximation approach

Evaluation Approach

Approximation

- $\mu_d(M-1, M) = \mu_M$
- $\zeta_d(M-1, M) = \zeta_M$

Pseudocode



```
procedure OUTER LOOP
    $\lambda_{min} := 0, \lambda_{max} := \min_{m \in [1,\dots,M]} \{\mu_m\}$
    repeat
        $\lambda := \frac{\lambda_{min}+\lambda_{max}}{2}$
        for $i = 1$ to $M$ do
            if $i = 1$ then
                $\mu_u(i,j) = \lambda, \zeta_u(i,j) = 0,01$
            else if $i > 1$ then
                $\mu_u(i,j) = \mu_i, \zeta_u(i,j) = c_i$
            end if
            $\mu_d(i,j) = \mu_j, \zeta_d(i,j) = c_j$
        end for
        procedure INNER LOOP
            for $i = 1$ to $M$ do
                if $i \neq 1$ then
                    Update $\mu_u(i,j), \zeta_u(i,j)$
                end if
                Update $p_S(i,j), p_B(i,j)$
            end for
      % Modification:
            for $j = M$ to $1$ do
                if $j = M$ then
                    $\mu_d(i,j) = \mu_j$, $\zeta_d(i,j) = \zeta_j$
                else
                    Update $\mu_d(i,j), \zeta_d(i,j)$
                end if
                Update $p_S(i,j), p_B(i,j)$
            end for
            return $WIP(\lambda)$, $X(\lambda)$
        end procedure
        if $WIP(\lambda) > n$ then
            $\lambda_{max} := \lambda$
        else
            $\lambda_{min} := \lambda$
        end if
    until $|WIP(\lambda) - N| \leq \epsilon$ or $\lambda_{max} - \lambda_{min} \leq 0,00001$
end procedure
```

Figure 5: Pseudocode

First Analytic Results

Approximation accuracy (industrial examples) - mean relative deviation of throughput

		Relative Deviation		
Example	Pallets	CV=0,5	CV=0,8	CV=1
Example 1	25 - 90	0.67%	1.01%	1.44%
Example 2	1 - 350	6.66%	5.89%	4.48%

Approximation accuracy (theoretical examples) - mean relative deviation of the throughput

Case	Pallets	Rel. Deviation	Rel. Deviation (Pallet Optimum)
BFDEx2b	4-41	0.45%	0.48% (29)
BFDEx2c	4-41	1.19%	1.00% (30)
BFDEx2d	4-41	1.01%	0.10% (28)

First Analytic Results

- Accurate results for a wide range of pallets
- Highest deviations for a small number of pallets
- Precise results for optimal pallet numbers

Managerial Implications

- Improvement of system throughput and reduction of the average WIP level
- Exceeding number of pallets only has a positive effect on the throughput
- First simulation results with a dynamic WIP reveal a robust optimal buffer allocation

Future Research

- Approximation of the throughput of a closed flow production system with a dynamic WIP level and deterministic processing times (random failure and repair times)
- Integration of the evaluation approaches into optimization models for the throughput and the average WIP

Throughput and Average WIP

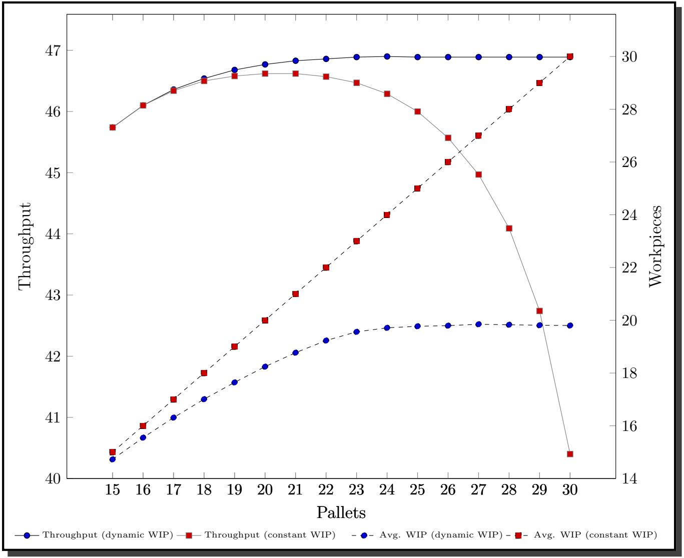


Figure 6: Throughput and average WIP