Dynamic Lead Time Based Control Point Policy for Multi Stage Manufacturing Systems

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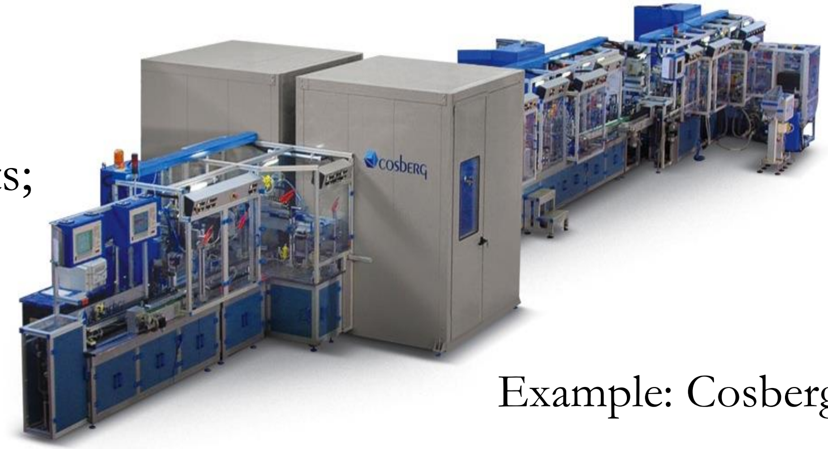
Industrial Motivation

Modern manufacturing systems needs:

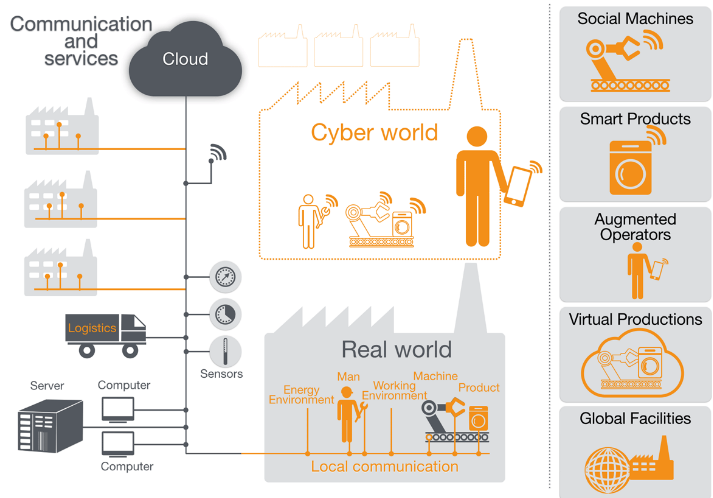
- Flexibility to produce many product variants;
- Small lot productions;
- Make-to-order.



Example: Cosberg.

Industrie 4.0 technological enablers:

- Data availability;
- Real-time observability of the system state;
- High capabilities to implement real-time scheduling policies.



Can the observability of the system state be exploited for a more effective real-time scheduling of make-to-order, multiple part types systems?

Production Control Policies

Surplus-based production control policies (single machine):

•**Kimemia, J., S.B. Gershwin.** 1983. An algorithm for the computer control of a flexible manufacturing system. *AIIE Transactions* 15(4) 353–362.

•**Bielecki, T., Kumar, P.R**. 1988, Optimality of zero-inventory policies for unreliable manufacturing systems, Operation Research, 36,4, 532-541.

Token-based production control policies:

•**Liberopoulos, G.** 2013. Production release control: Paced, wip-based or demand-driven? revisiting the push/pull and make-to-order/make-to-stock distinctions. Springer, ed., *Handbook of Stochastic Models and Analysis of Manufacturing System Operations*, vol. 192. 211–247.

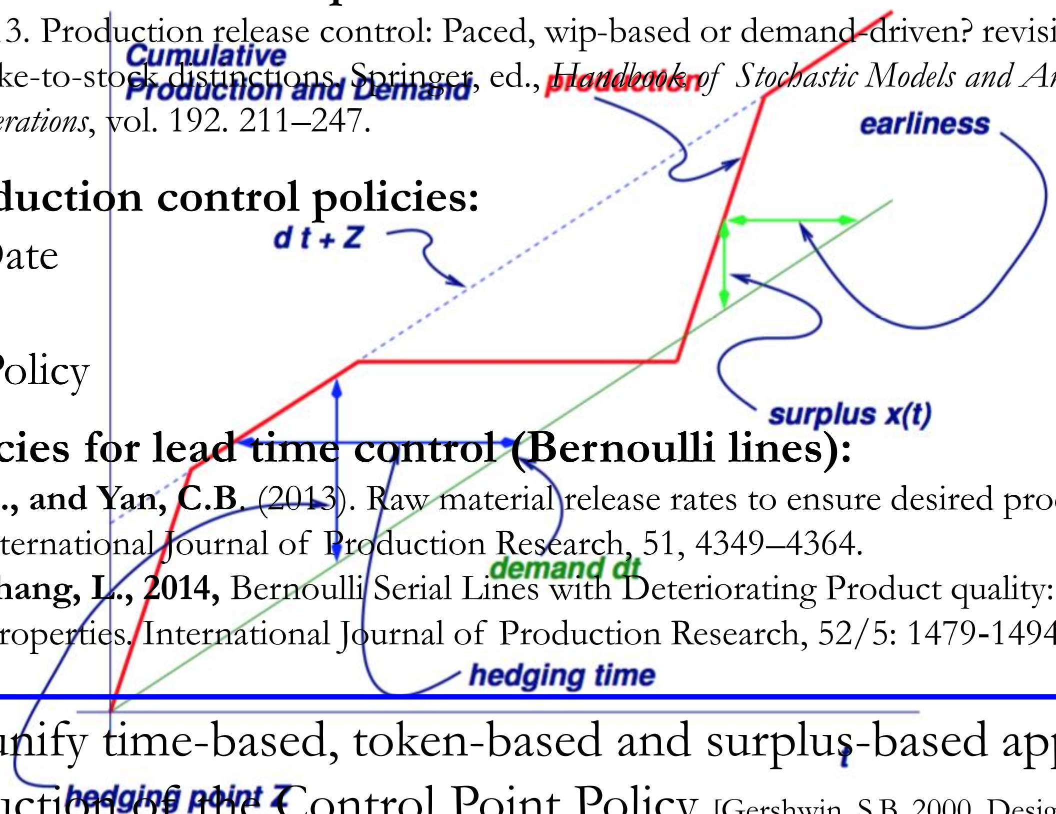
Time-based production control policies:

- Earliest Due Date
- Least Slack
- Critical Ratio Policy

Part-release policies for lead time control (Bernoulli lines):

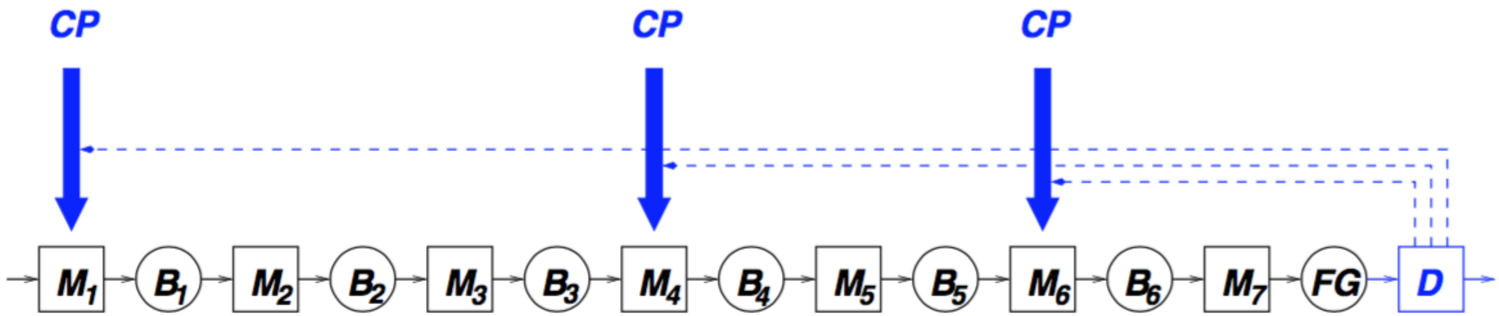
•**Biller, S., Meerkov, S., and Yan, C.B**. (2013). Raw material release rates to ensure desired production lead time in bernoulli serial lines. International Journal of Production Research, 51, 4349–4364.

•**Naebulharam, R., Zhang, L., 2014,** Bernoulli Serial Lines with Deteriorating Product quality: Performance Evaluation and System-theoretic Properties. International Journal of Production Research, 52/5: 1479-1494.



An attempt to unify time-based, token-based and surplus-based approach was done with the introduction of the Control Point Policy [Gershwin, S.B. 2000. Design and operation of manufacturing systems: the control-point policy. *IIE Transactions* 32(10) 891–906].

The Control Point Policy (CPP) – Time-based version



CPP control

Features:

- Multi-stage lines.
- Unreliable Machines.
- Multiple part types (different importance).

Real-time scheduling policy:

At each control point, whenever the machine becomes available, work on the highest ranking part that is ready. If no parts are ready, wait until a new part arrives or when an available part becomes ready.

A **control point** is a machine where the policy is applied.

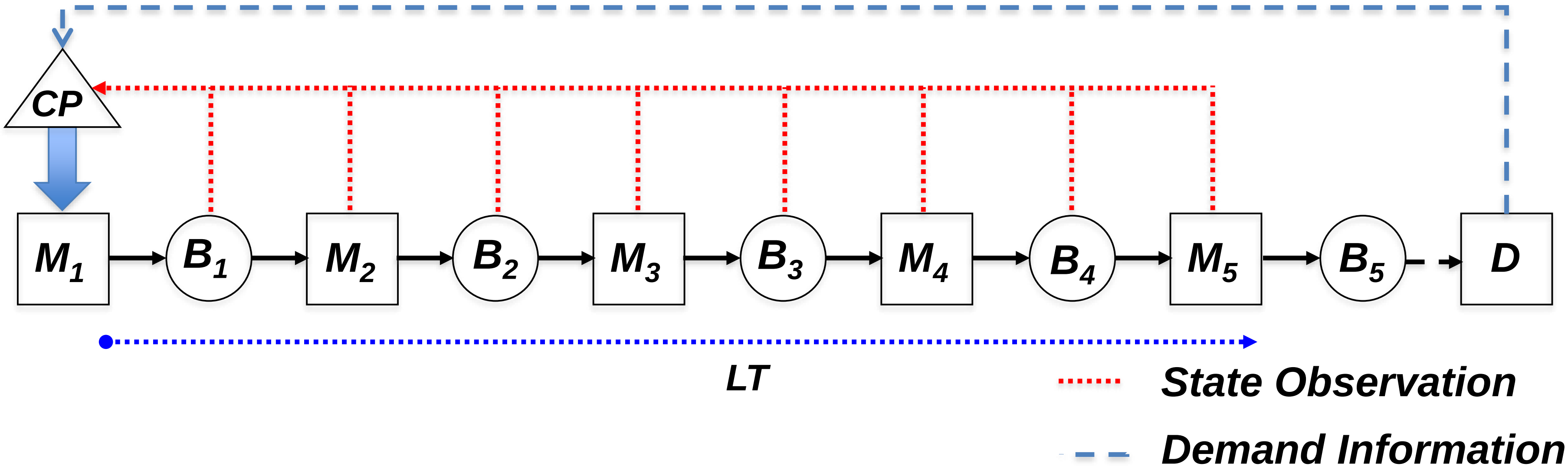
- A **hedging time** is a conservative estimate of the lead time between the control point and the finished product buffer. In previous formulations, the hedging time was a constant parameter.
- A part is **available** at a control point if it is present and not blocked.
- A part is **ready** if it is available and:

The hedging times need to be optimized by simulation or analytical methods [Vericourt, F., S.B. Gershwin. 2004. Performance evaluation of a make-to-stock production line with a two- parameter-per-machine policy: the control point policy. *IIE Transactions* 36(3) 221–236.]

the current time + the hedging time ≥ the due date

$$t + Z \geq D$$

Objectives: new dynamic, state-based CPP

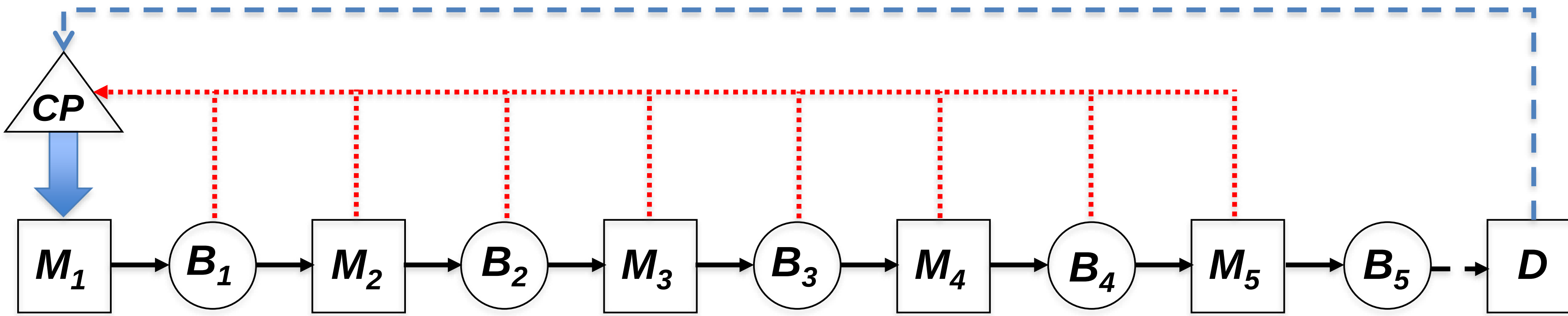


Innovation sources:

- The hedging times are functions of the state of the system.
  - When the system is poorly populated: smaller hedging times.
  - When the system is highly populated: larger hedging times.
- The hedging times are calculated as target quantiles of the lead time distribution.

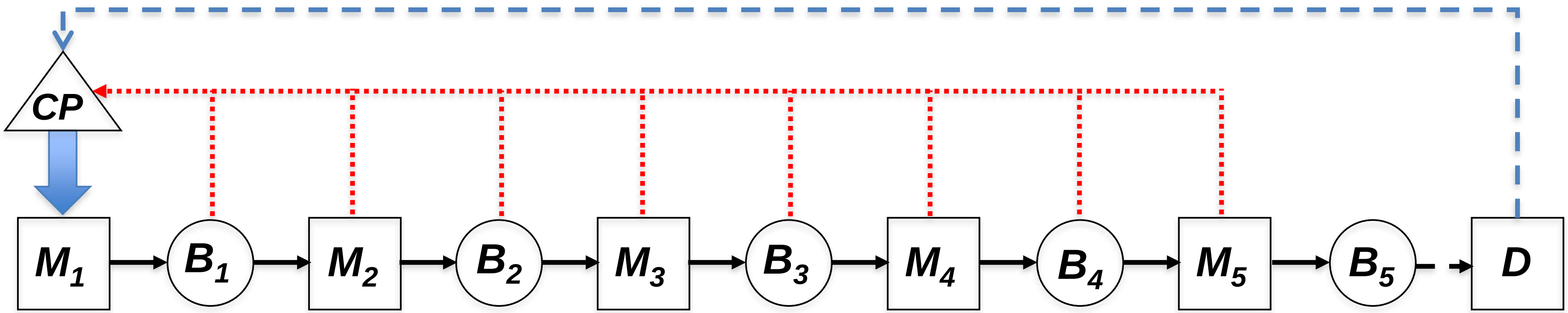
The goal is to meet target service levels while minimizing the inventory

Modelling Assumptions – System Features



- Linear system with K unreliable machines and K-1 buffers of finite capacity N_k.
- An infinite capacity buffer, B_K, store finished parts with early delivery.
- The flow of material in the system is <u>discrete</u>. Processing times are scaled to the time unit and are identical at different stages.
- The first machine, M_1, where loading decisions are made, is reliable and its operation time is 1.
- Machine M_k, k=2,..K, fail with probability p_k, and is repaired, once failed, with probability r_k.
- The system state can be described by the vector $s=(n_1,n_2,..,n_{K-1}, \alpha_2,.., \alpha_K)$. The set of states is denoted as S. The generic system state at time unit t is denoted as s_t.

Modelling Assumptions – Part types



- In a finite time horizon, the system is assigned a batch of B parts to produce. The vector Q of size X, represents the number of parts of type x=1,..X to be produced. For simplicity, the vector R of size B indicates the part type to which part b belongs.
- The system processes X part types, x=1,..,X. The part type 1 has the highest importance, part type 2 the second highest importance, and so on.
- For each part b in the batch, a due date D_b is assigned.
- At each time unit, a maximum lot size of 1 part can be loaded to the system.
- Set-up times while switching among parts are set to zero.
- A single control point is considered.

Modelling Assumptions – Dynamic CPP

At the beginning of each time unit, t, the CPP defines one of the following actions:

- Load the **ready** part b of highest priority at M_1 and start the processing.
- If no part is ready or $n_1=N_1$, then do nothing.

The policy acts only on parts that are **ready**. A part b is said to be ready if:

$$t + Z_{R(b),s_t} \geq D_b \qquad p(LT(s_t) > Z_{R(b),s_t}) \leq \gamma_{R(b)}$$

where $LT(s_t)$ is the lead time when the system is in state s_t, conditioned to the loading of the part. γ_x is a fixed quantile of the lead time distribution.

The dynamic CPP has X parameters to be determined (γ_x)

The lead time distribution conditioned on the system state needs to be computed.

Performance Measures

- The total tardiness **TT**, of the batch, calculated as the sum of the delay of parts with late delivery:

$$TT = \sum_{b=1}^{B} (E_b - D_b) I_b$$

Where E_b is the time unit at which part b is released in the finished parts buffer B_K, and I_b is an indicator function assuming value 1 if $E_b > D_b$.

- The total earliness, **TE**, of the batch, calculated as the sum of the time units parts with early delivery spend in the finished parts buffer, B_K.

$$TE = \sum_{b=1}^{B} (D_b - E_b)(1 - I_b)$$

Performance Measures

- The service level, **SL**, of the system, i.e. the fraction of parts delivered on time.

- The service level of part type x, $\mathbf{SL_x}$.

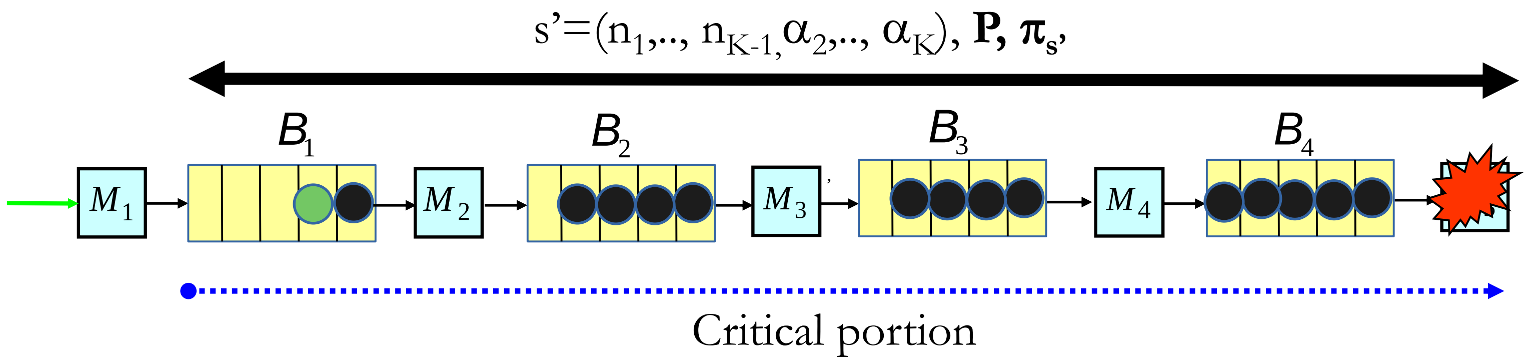
- The throughput, **TH**, calculated as:

$$TH = \frac{\max(E_b)}{B}$$

- The average Total Inventory, **WIP**, considering both the inter-stage inventory and the final parts inventory, used to store parts delivered before the due-date.

Calculation of the lead time distribution

Colledani M., Gershwin S.-B., Angius A., Horvath A., "*Lead Time Dependent Product Deterioration in Manufacturing Systems with Serial, Assembly and Closed-loop Layout*", 10th Conference on Stochastic Models of Manufacturing And Service Operations, 1-6 June, 2015, Volos, Greece.



- Denote by $\pi_{s',n}$ the transient probabilities after n steps, starting from state s':

$$\pi_{s',n} = \pi_{s'} P^n$$

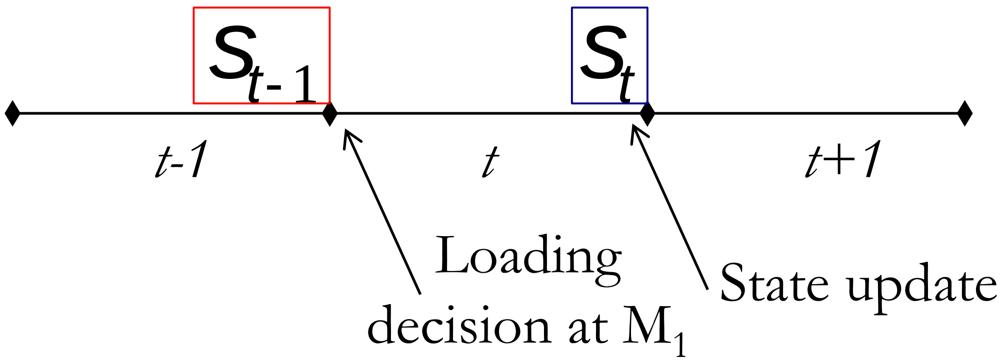
- The lead time distribution is:

$$\mathrm{P}(LT(s') \le n) = \pi_{s',n}(s_{empty})$$

Where s_{empty} is the state in which ($n_1=0$, $n_2=0$, $n_{k-1}=0$, $\alpha_2=1$,.., $\alpha_K=1$).

Calculation of the hedging times

- Lead time distribution, conditional to the loading of a part at time *t*.



$$P(LT(s_t) \le n) = \sum_{\forall s' \in S} \lambda(s_{t-1}, s') P(LT(s') \le n)$$

Where $\lambda(s_{t-1},s')$ is the probability of making a transition in one time unit from state s_{t-1} to state s' by loading a part at M_1.

- The hedging times $Z_{x,st}$ for each part type can be computed as:

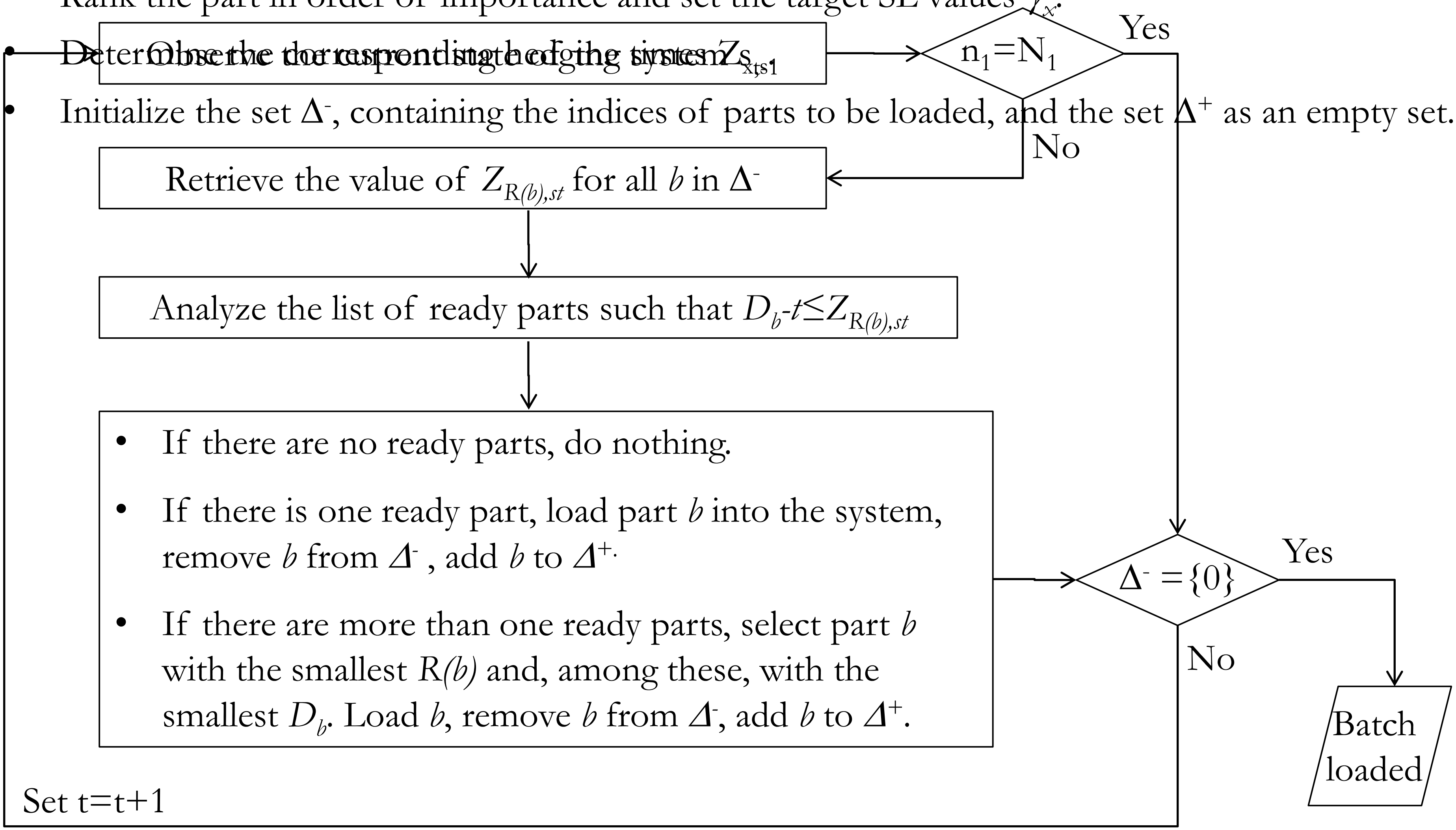
$$P(LT(s_t) > Z_{x,s_t}) \le g_x$$

Dynamic CPP algorithm

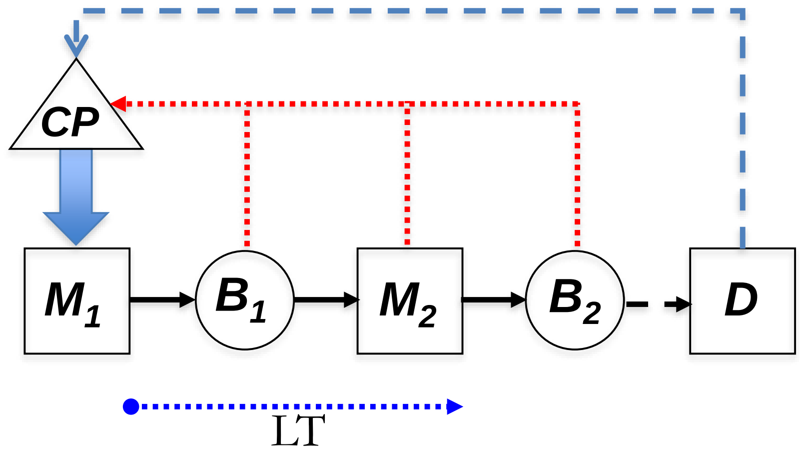
Preparation phase:

- Rank the part in order of importance and set the target SL values γ_x.
- Determine the corresponding hedging times $Z_{x,ts1}$.
- Initialize the set Δ^-, containing the indices of parts to be loaded, and the set Δ^+ as an empty set.

Real time execution phase (at the generic time time unit t>0):



Numerical Results



The **D-CPP** policy is compared with the following policies:

- **EDDP** (Earliest Due Date Policy), neglecting the part type importance.
- **EDDP-IR** (with Importance Ranking): Applies EDDP to all parts of type 1, then 2, and so on.

Questions:

- How does the D-CPP behave if compared to the other policies?
- How does the SL behaves with respect to the assigned target value γ_x?
- How does the system saturation level affects the performance of the policy?

Numerical Results – single part type

- *B=200*, *γ=0.95*, *l=d/E*, where *E* is the throughput of the saturated system, *l* is the saturation level, and *d* is the demand rate (Poisson process).

ID	p_2	r_2	e_2	l	Policy	SL	WIP	TE	TT	TH
1	0.001	0.01	0.909	0.3	D-CPP	0.971 ± 0.005	0.64 ± 0.05	86 ± 1	676 ± 25	0.26
					EDDP	0.994 ± 0.002	72.59 ± 0.5	56880 ± 370	79 ± 5	0.9
2	0.001	0.01	0.909	0.8	D-CPP	0.93 ± 0.01	1.87 ± 0.11	178 ± 1	1407 ± 50	0.67
					EDDP	0.929 ± 0.011	25.66 ± 0.33	7180 ± 124	1290 ± 34	0.9
3	0.001	0.02	0.952	0.3	D-CPP	0.985 ± 0.003	0.561 ± 0.03	111 ± 1	157 ± 5	0.28
					EDDP	0.997 ± 0.002	69.29 ± 0.38	49724 ± 225	12 ± 1	0.95
4	0.001	0.02	0.952	0.8	D-CPP	0.93 ± 0.011	2.02 ± 0.09	167 ± 2	745 ± 20	0.76
					EDDP	0.931 ± 0.012	19.96 ± 0.21	4856 ± 88	689 ± 17	0.95
5	0.0001	0.002	0.952	0.3	D-CPP	0.989 ± 0.005	0.559 ± 0.06	112 ± 1	1147 ± 130	0.28
					EDDP	0.995 ± 0.003	67.13 ± 0.3	50953 ± 270	383 ± 24	0.95
6	0.0001	0.002	0.952	0.8	D-CPP	0.982 ± 0.005	1.6 ± 0.06	177 ± 1	1035 ± 69	0.76
					EDDP	0.983 ± 0.004	20.97 ± 0.1	5339 ± 37	2001 ± 52	0.95

- The D-CPP outperforms the EDDP in terms of WIP (savings in the range **-89%,-99%**).
- For low saturation levels (*l=0.3*): the target service level is met.
- For high saturation levels (*l=0.8*): the service level of the D-CPP drops below the target level but remains comparable to the EDDP. Why?

Numerical Results – single part type

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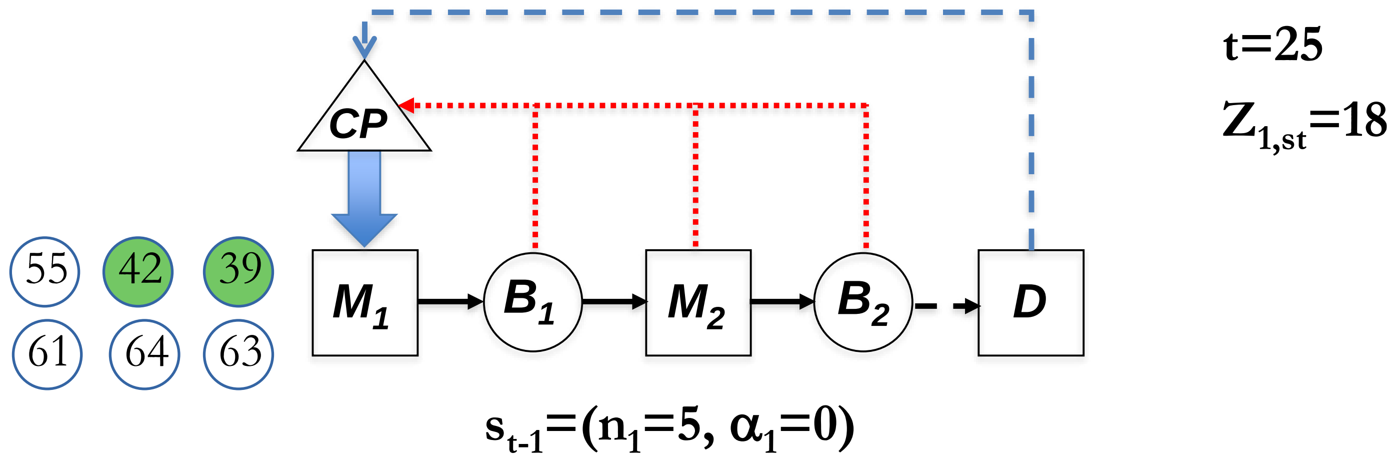

For higher saturation level, the probability of having more than one ready parts increases, thus reducing the service level of the D-CPP policy.

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- The D-CPP outperforms the EDDP in terms of WIP (savings in the range **-89%,-99%**).
- For low saturation levels (*l=0.3*): the target service level is met. For high saturation levels (*l=0.8*): the service level of the D-CPP drops below the target level but remains comparable to the EDDP.
- The D-CPP behaves better for higher variability cases.

Numerical Results – multiple part types

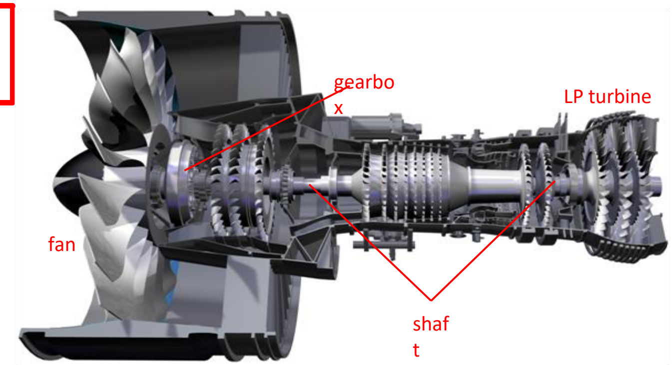
- $p=0.001$, $r=0.01$. $\gamma_x=0.95$ for each part type.

ID	X	B	Q	l	Policy	SL_1	SL_2	SL_3	WIP
1	3	1000	[100, 600, 300]	0.7	D-CPP	0.977 ± 0.012	0.932 ± 0.013	0.457 ± 0.007	1.54 ± 0.13
					EDDP	0.97 ± 0.013	0.968 ± 0.013	0.968 ± 0.013	124.97 ± 2.28
					EDDP-IR	0.995 ± 0.001	0.835 ± 0.012	0.32 ± 0.008	196.45 ± 3.35
2	3	1000	[100, 600, 300]	0.8	D-CPP	0.975 ± 0.009	0.921 ± 0.009	0.224 ± 0.002	1.96 ± 0.12
					EDDP	0.925 ± 0.017	0.925 ± 0.015	0.924 ± 0.015	77.86 ± 2.31
					EDDP-IR	0.995 ± 0.001	0.773 ± 0.014	0.135 ± 0.003	170 ± 3
3	3	1000	[100, 600, 300]	0.9	D-CPP	0.958 ± 0.014	0.918 ± 0.014	0.147 ± 0.003	2.35 ± 0.17
					EDDP	0.915 ± 0.017	0.891 ± 0.016	0.862 ± 0.015	28.029 ± 0.67
					EDDP-IR	0.994 ± 0.002	0.718 ± 0.013	0.114 ± 0.004	125.09 ± 2.79
4	5	1000	[50, 200, 600, 50, 100]	0.9	D-CPP	0.947 ± 0.017	0.921 ± 0.017	0.453 ± 0.005	2.42 ± 0.18
					EDDP	0.927 ± 0.018	0.884 ± 0.017	0.898 ± 0.016	52.45 ± 01.2
					EDDP-IR	0.997 ± 0.001	0.885 ± 0.009	0.189 ± 0.005	161 ± 2.6

- The proposed D-CPP always provides the target Service Level for the highest priority part, also for high saturation cases ($l=0.9$).
- D-CPP always performs better than the EDDP and worse than the EDDP-IR in terms of part type 1 Service Level.
- However, the D-CPP always performs better than the EDDP-IR for lower priority parts.
- The D-CPP outperforms both policies in terms of WIP (savings in the range **-92%,-99%**).

Dynamic CPP – application scenario

Production of shafts in the aeronautics sector.



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Problem:

- Mutiple shaft types, very expensive parts.
- Several machining-measurement-rework loops cause stochastic processing times and routing.
- Long lead times, large inventory and operational costs.

Conclusions

Major findings:

- Formulation of a new dynamic, state-based Control Point Policy.
- Derivation of the lead time distribution conditional to the loading policy.
- Analysis of the impact of the proposed policy on the system performance in simple cases.

Future Research:

- Wider experimental analysis to prove the benefits of the policy.
- Extension to multiple distributed Control Points.
- Extension to non-linear systems and systems with part type dependent routings.
- Analytical derivation of the system behavior operating under the proposed state-dependent Control Point Policy.

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