SMA 6304 / MIT 2.853 / MIT 2.854

Manufacturing Systems

Lecture 24-25: Multi-Stage Control and Scheduling

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Definitions

- Events may be *controllable* or not, and *predictable* or not.

	controllable	*uncontrollable*
predictable	loading a part	lunch
unpredictable	???	machine failure

Definitions

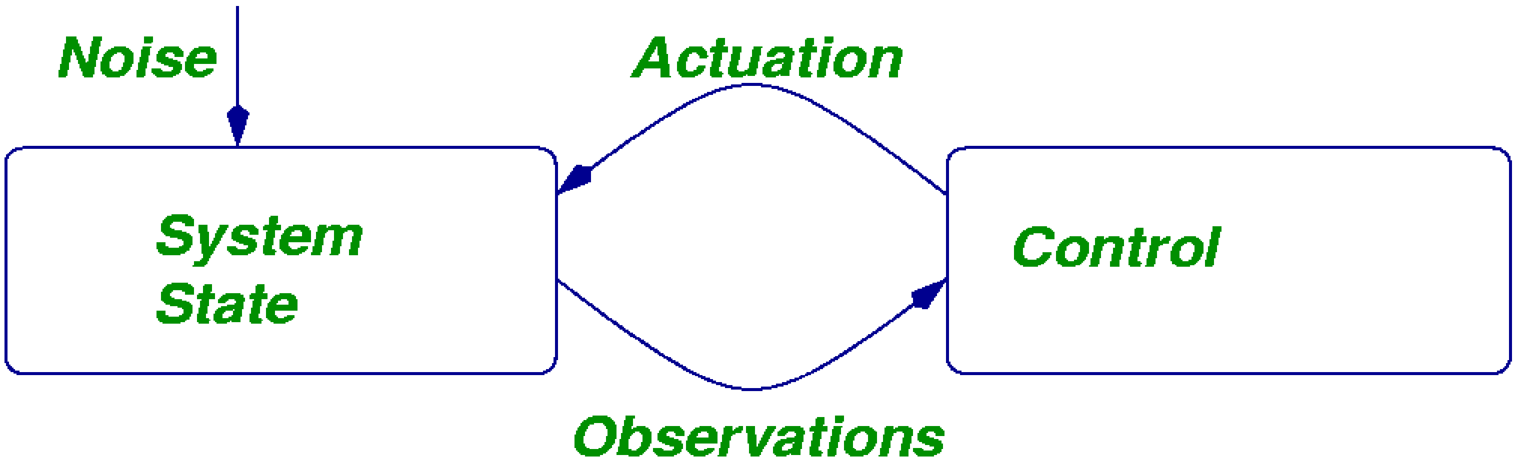
- *Scheduling is the selection of times for future controllable events.*
- Ideally, scheduling systems should deal with *all* controllable events, and not just production.
  - ★ That is, they should select times for operations, set-up changes, preventive maintenance, etc.

Definitions

- Because of recurring random events, scheduling is an on-going process, and not a one-time calculation.
- Scheduling, or shop floor control, is the bottom of the scheduling/planning hierarchy. It translates *plans* into *events.*

Definitions

Control Paradigm



This is the general paradigm for control theory and engineering.

Definitions

In a factory,

- *State:* distribution of inventory, repair/failure states of machines, etc.
- *Control:* move a part to a machine and start operation; begin preventive maintenance, etc.
- *Noise:* machine failures, change in demand, etc.

Definitions

- *Release:* Authorizing a job for production, or allowing a raw part onto the factory floor.
- *Dispatch:* Moving a part into a workstation or machine.
- *Release is more important than dispatch.* That is, improving release has more impact than improving dispatch, if both are reasonable.

Definitions

Requirements

Scheduling systems or methods should ...

- deliver good factory performance.
- compute decisions quickly, in response to changing conditions.

Performance Goals

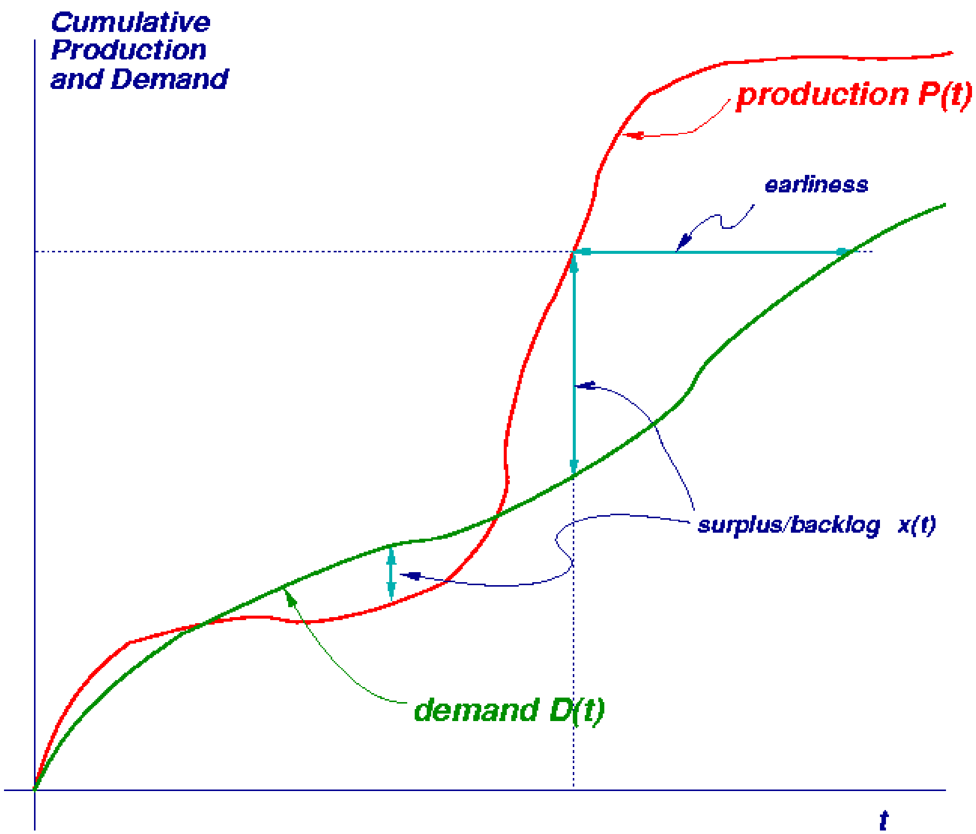
- To minimize inventory and backlog.
- To maximize probability that customers are satisfied.
- To maximize predictability (ie, minimize performance variability).

Performance Goals

- For MTO
  - ⋆ To meet delivery promises.
  - ⋆ To make delivery promises that are both *soon* and *reliable* .
- For MTS
  - ⋆ to have FG available when customers arrive; and
  - ⋆ to have minimal FG inventory.

Performance Goals

Objective of Scheduling



Objective is to keep cumulative production close to cumulative demand.

Performance Goals

Difficulties

- Complex factories
- Unpredictable demand (ie $\boldsymbol{D}$ uncertainty)
- Factory unreliability (ie $\boldsymbol{P}$ uncontrollability)

Basic approaches

- Simple rules — *heuristics*
  - ⋆ Dangers:
    - ∗ Too simple — may ignore important features.
    - ∗ Rule proliferation.
- Detailed calculations
  - ⋆ Dangers:
    - ∗ Too complex — impossible to develop intuition.
    - ∗ Rigid — had to modify — may have to lie in data.

- Deterministic optimization.
  - ⋆ Large linear or mixed integer program.
  - ⋆ Re-optimize periodically or after important event.
- Scheduling by simulation.

Basic approaches

Detailed calculations

Dangers

- Nervousness or scheduling volatility (fast but inaccurate response):
  - ⋆ The optimum may be very flat. That is, many very different schedule alternatives may produce similar performance.
  - ⋆ A small change of conditions may therefore cause the optimal schedule to change substantially.

Basic approaches

Detailed calculations

Dangers

- Slow response:
  - ⋆ Long computation time.
  - ⋆ Freezing.
- Bad data:
  - ⋆ Factory data is often very poor, especially when workers are required to collect it manually.
  - ⋆ GIGO

Heuristics

Characteristics

- A *heuristic* is a proposed solution to a problem that *seems* reasonable but cannot be rigorously justified.
- In reentrant systems, heuristics tend to favor *older* parts.
  - ⋆ This keeps inventory low.

Heuristics

Characteristics

Desirable Characteristics

- Good heuristics deliver good performance.
- Heuristics tend to be simple and intuitive.
  - ★ People should be able to understand why choices are made, and anticipate what will happen.
  - ★ Relevant information should be simple and easy to get access to.
  - ★ Simplicity helps the development of simulations.

Heuristics

Characteristics

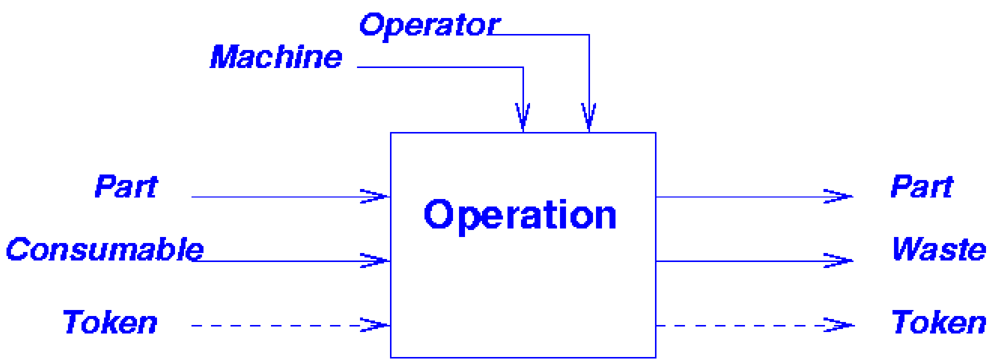
Decentralization

- It is often desirable for people to make decisions on the basis of local, current information.
  - ⋆ Centralized decision-making is most often bureaucratic, slow, and inflexible.
- Most heuristics are naturally decentralized, or can be implemented in a decentralized fashion.

Heuristics

Material/token policies

Performance evaluation



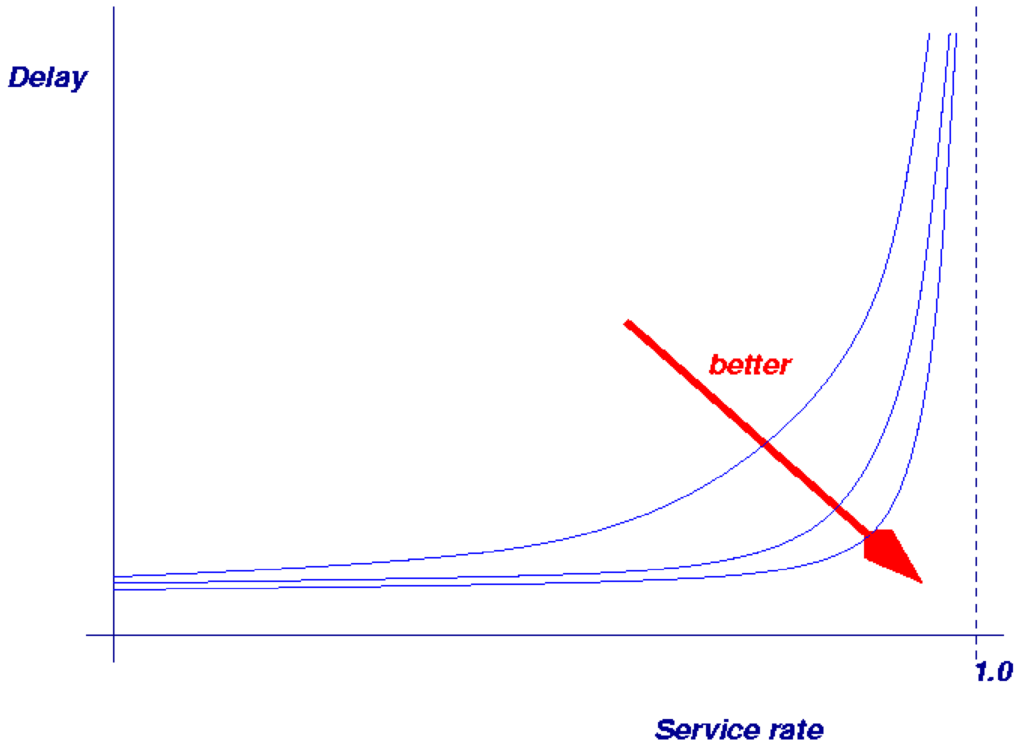
- An operation cannot take place unless there is a token available.
- Tokens *authorize* production.

- These policies can often be implemented *either* with finite buffer space, or a finite number of tokens. Mixtures are also possible.
- Buffer space could be shelf space, or floor space indicated with paint or tape.

Heuristics

Material/token policies

Performance evaluation

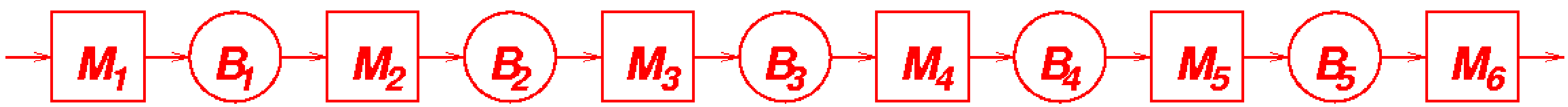


- Tradeoff between service rate and average cycle time.

Heuristics

Material/token policies

Finite buffer

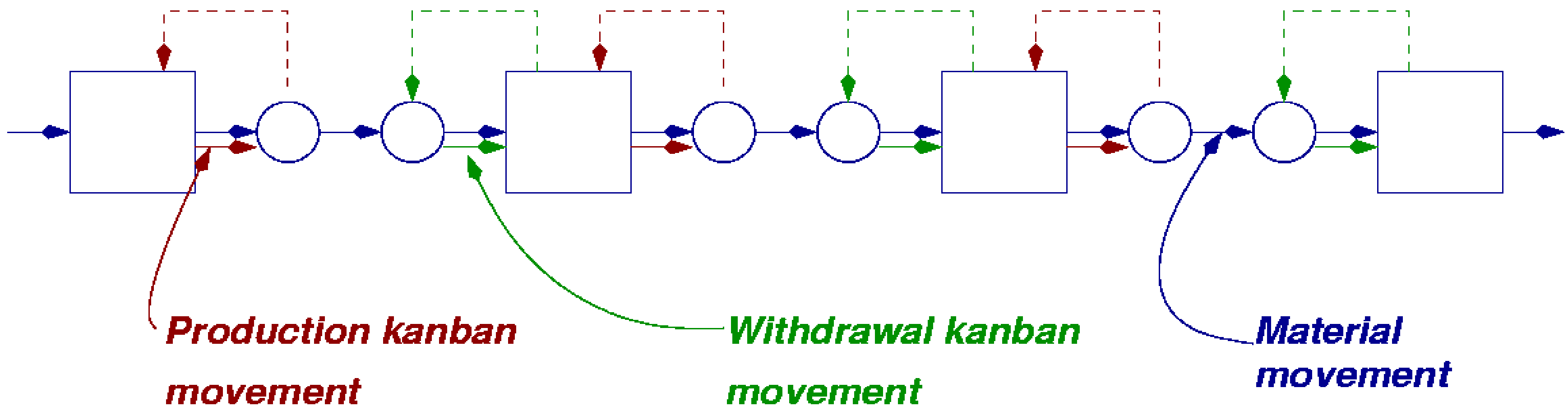


- Buffers tend to be close to full.
- Sizes of buffers should be related to magnitude of disruptions.
- Not practical for large systems, unless each box represents a *set* of machines.

Heuristics

Material/token policies

Kanban



- Performance slightly better than finite buffer.
- Sizes of buffers should be related to magnitude of disruptions.

Heuristics

Material/token policies

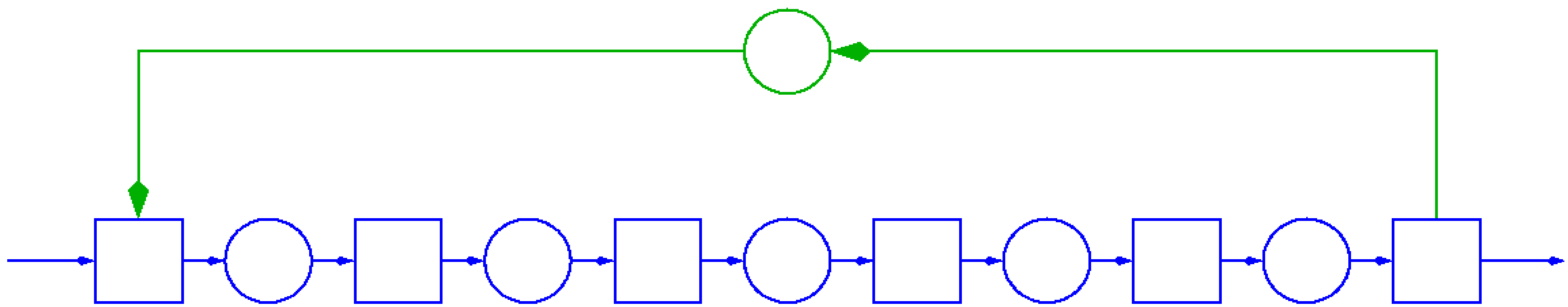
CONWIP

- *Constant Work in Progress*
- Variation on kanban in which the number of parts in an area is limited.
- When the limit is reached, no new part enters until a part leaves.
- Variations:
  - ★ When there are multiple part types, limit work hours or dollars rather than number of parts.
  - ★ Or establish individual limits for each part type.

Heuristics

Material/token policies

CONWIP



- If token buffer is not empty, attach a token to a part when M_1 starts working on it.
- If token buffer is empty, do not allow part into M_1.
- Token and part travel together until they reach last machine.
- When last machine completes work on a part, the part leaves and the token moves to the token buffer.

Heuristics

Material/token policies

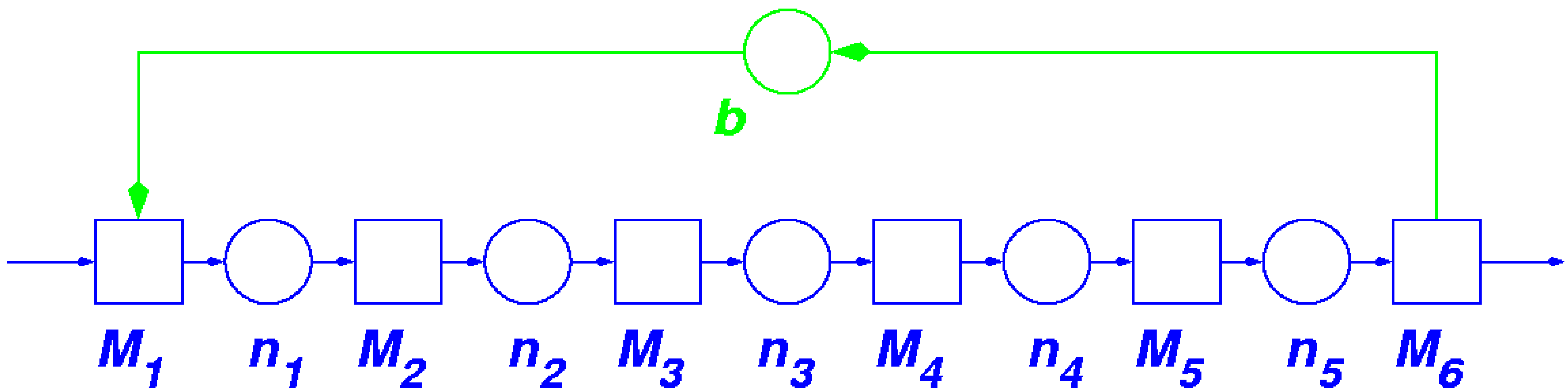
CONWIP

- Infinite material buffers.
- Infinite token buffer.
- Limited material population at all times.
- Population limit should be related to magnitude of disruptions.

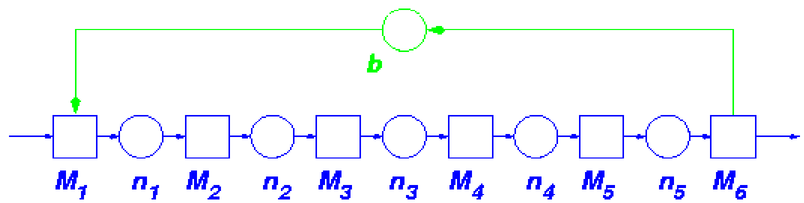
Heuristics

Material/token policies

CONWIP



- *Claim:* $n_1 + n_2 + ... + n_6 + b$ is constant.

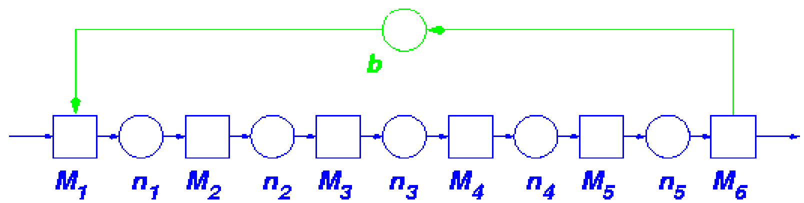


- Define $C = n_1 + n_2 + ... + n_5 + b$.
- Whenever M_j does an operation, C is unchanged, $j = 2, ..., 5$.
  - ⋆ ... because n_{j-1} goes down by 1 and n_j goes up by 1, and nothing else changes.
- Whenever M_1 does an operation, C is unchanged.
  - ⋆ ... because b goes down by 1 and n_1 goes up by 1, and nothing else changes.

Heuristics

Material/token policies

CONWIP Proof

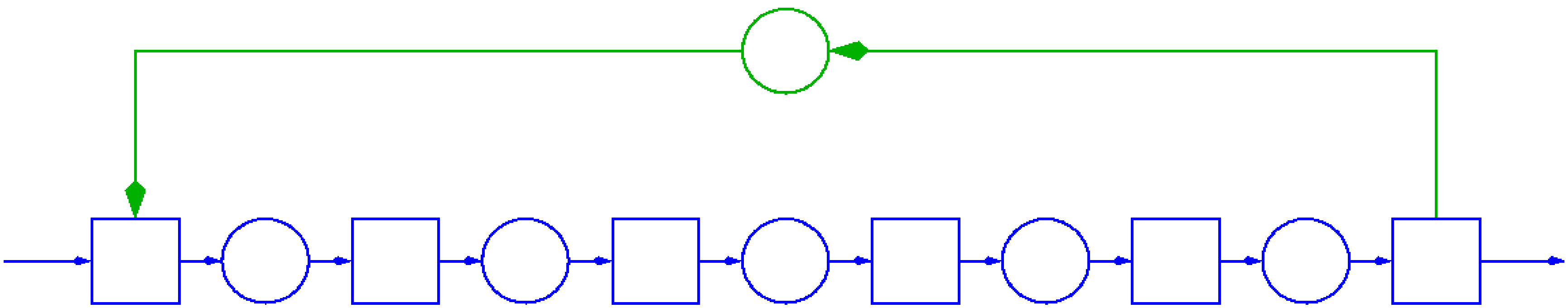


- Whenever M_6 does an operation, C is unchanged.
  - ⋆ ... because n_5 goes down by 1 and b goes up by 1, and nothing else changes.
- That is, whenever *anything* happens, $C = n_1 + n_2 + ... + n_5 + b$ is unchanged.
- C is an *invariant* .
- Here, C is the maximum population of the material in the system.

Heuristics

Material/token policies

CONWIP/Kanban Hybrid

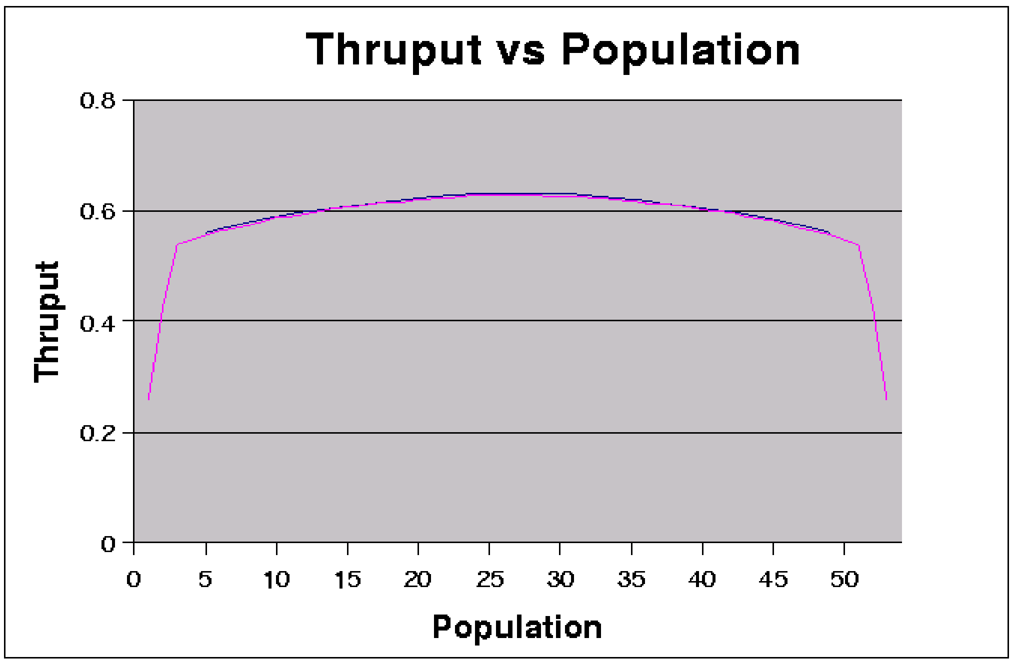


- Finite buffers
- Finite material population
- Limited material population at all times.
- Population and sizes of buffers should be related to magnitude of disruptions.

Heuristics

Material/token policies

CONWIP/Kanban Hybrid

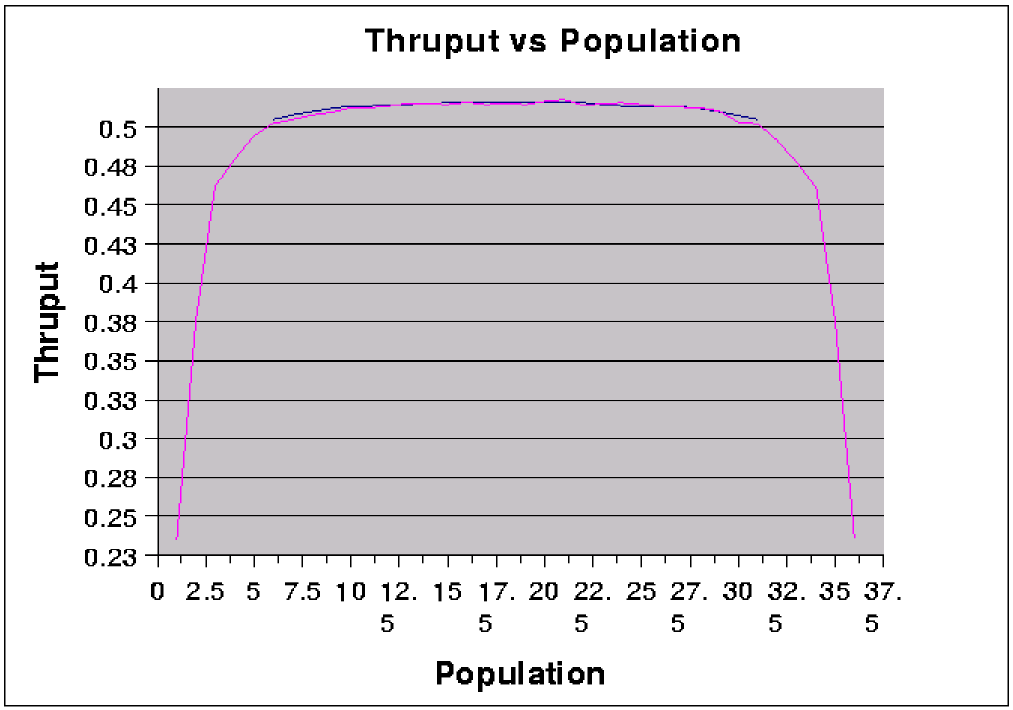


- Production rate as a function of CONWIP population.
- In these graphs, total buffer space (including for tokens) is finite.

Heuristics

Material/token policies

CONWIP/Kanban Hybrid

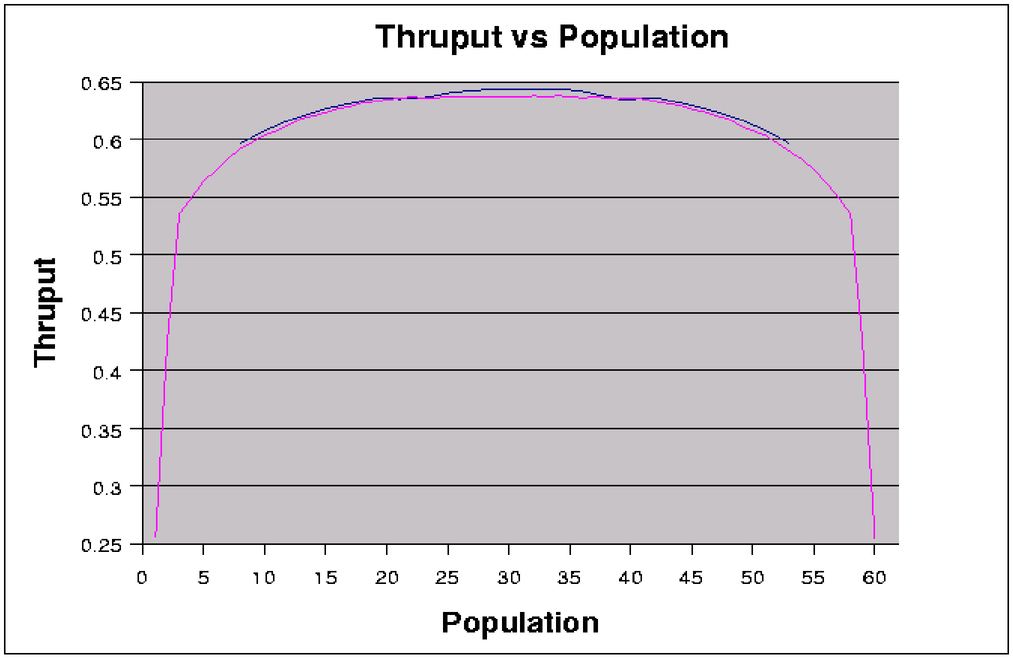


- Maximum production rate occurs when population is half of total space.

Heuristics

Material/token policies

CONWIP/Kanban Hybrid

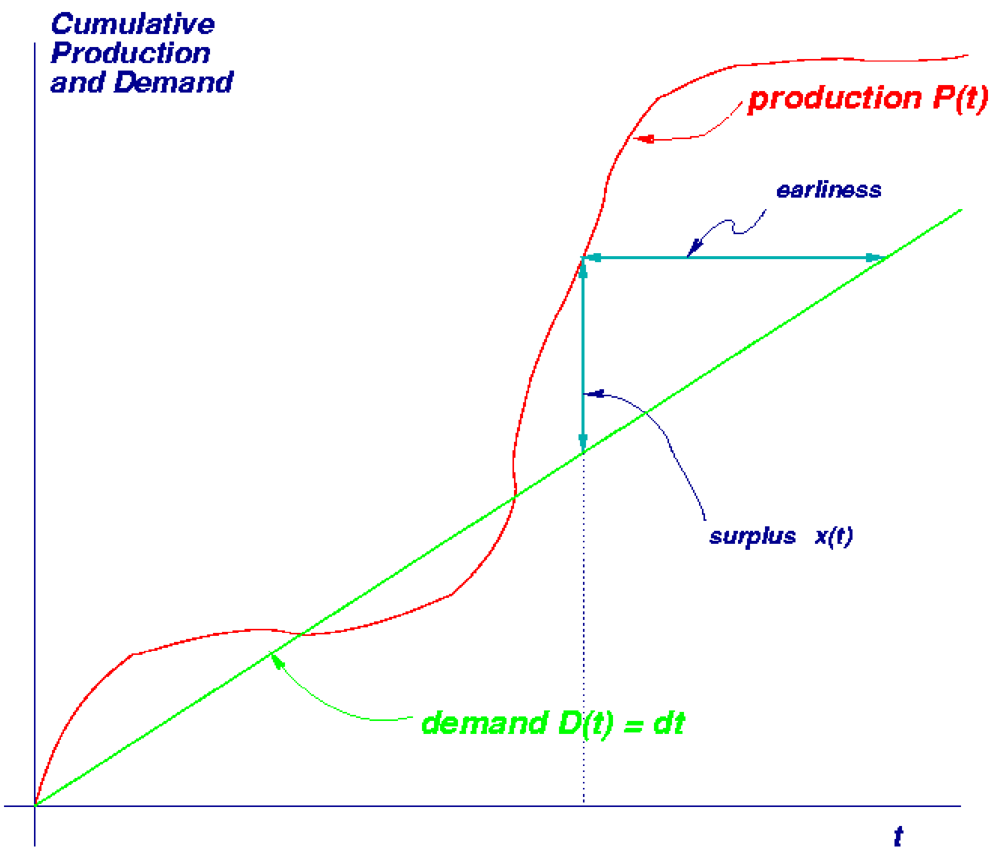


- When total space is infinite, production rate increases only.

Simple Policies

Material/token policies

Hedging point



- *State:* (x, α)
- x = surplus = difference between cumulative production and demand
- α = machine state. $\alpha = 1$ means machine is up; $\alpha = 0$ means machine is down.

Simple Policies

Material/token policies

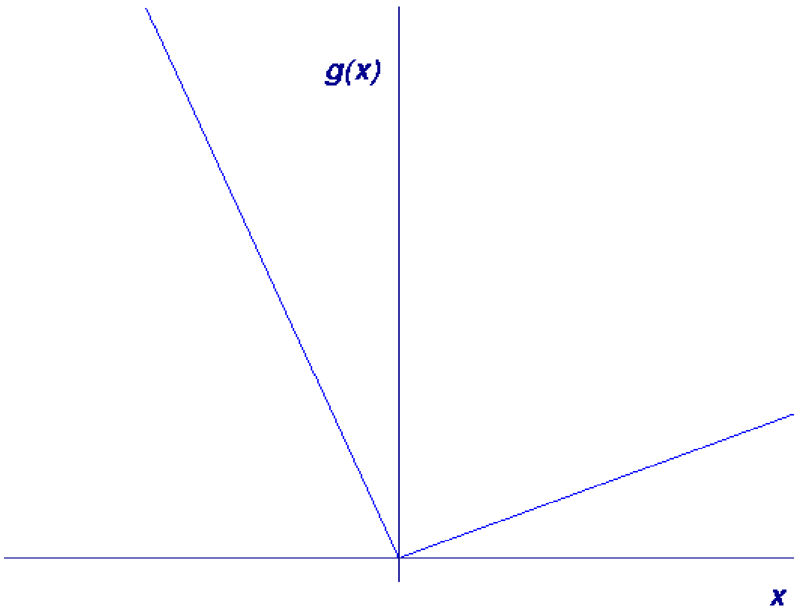
Hedging point

- *Control:* u
- u = short term production rate.
  - $\star$ if $\alpha = 1$, $0 \leq u \leq \mu$;
  - $\star$ if $\alpha = 0$, $u = 0$.

Simple Policies

Material/token policies

Hedging point



- Objective function:

$$\min E \int_0^T g(x(t))dt$$

- where

$$g(x) = \begin{cases} g_+ x, & \text{if } x \geq 0 \\ -g_- x, & \text{if } x < 0 \end{cases}$$

Simple Policies

Material/token policies

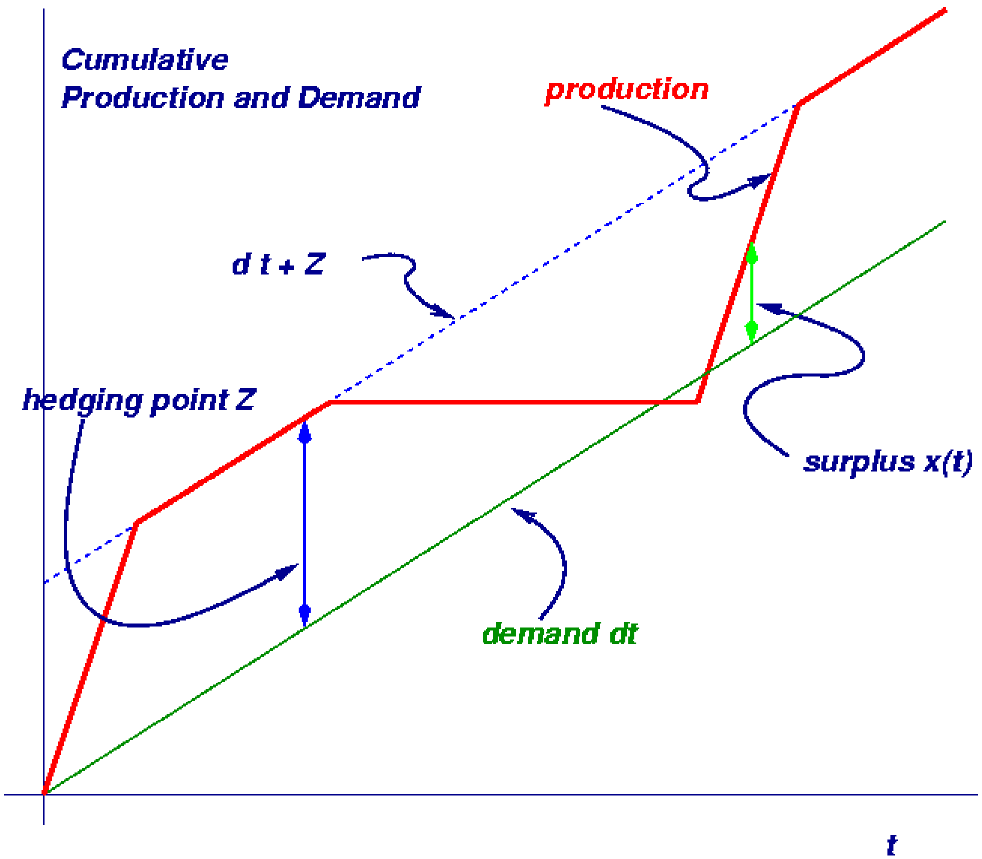
Hedging point

- Dynamics:
  - ⋆ $\dfrac{dx}{dt} = u - d$
  - ⋆ α goes from 0 to 1 according to an exponential distribution with parameter r.
  - ⋆ α goes from 1 to 0 according to an exponential distribution with parameter p.

Simple Policies

Material/token policies

Hedging point



Solution:

- if $x(t) > Z$, wait;
- if $x(t) = Z$, operate at demand rate d;
- if $x(t) < Z$, operate at maximum rate μ.

Simple Policies

Material/token policies

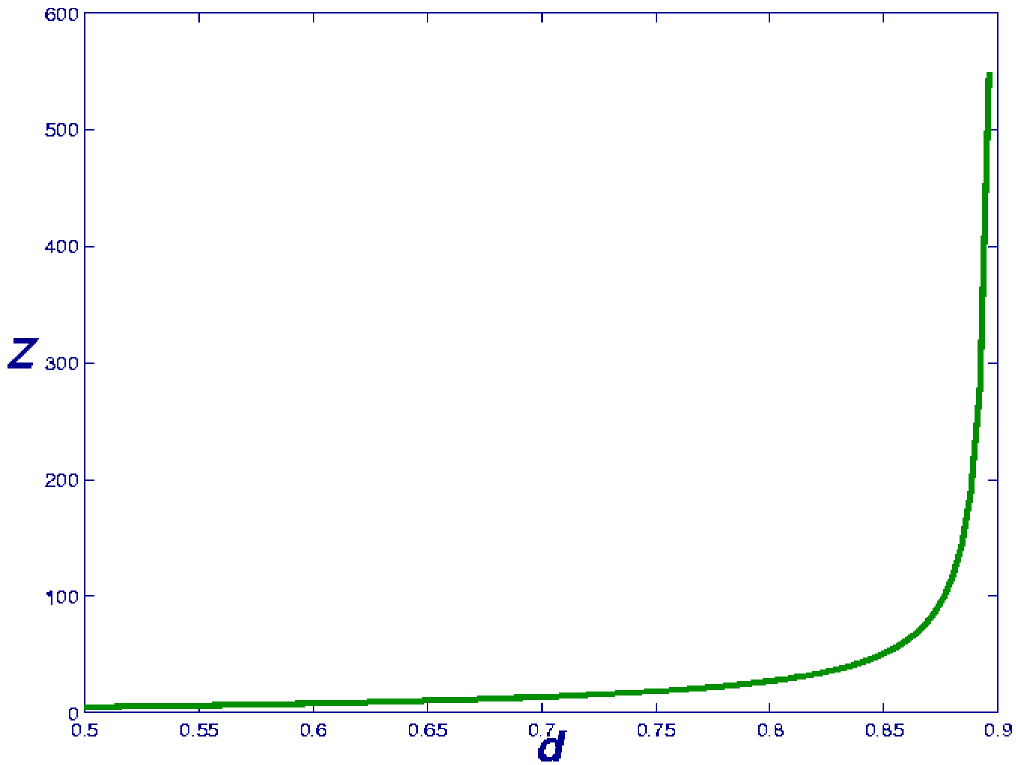
Hedging point

- The hedging point Z is the single parameter.
- It represents a trade-off between costs of inventory and risk of disappointing customers.
- It is a function of d, μ, r, p, g_+, g_-.

Simple Policies

Material/token policies

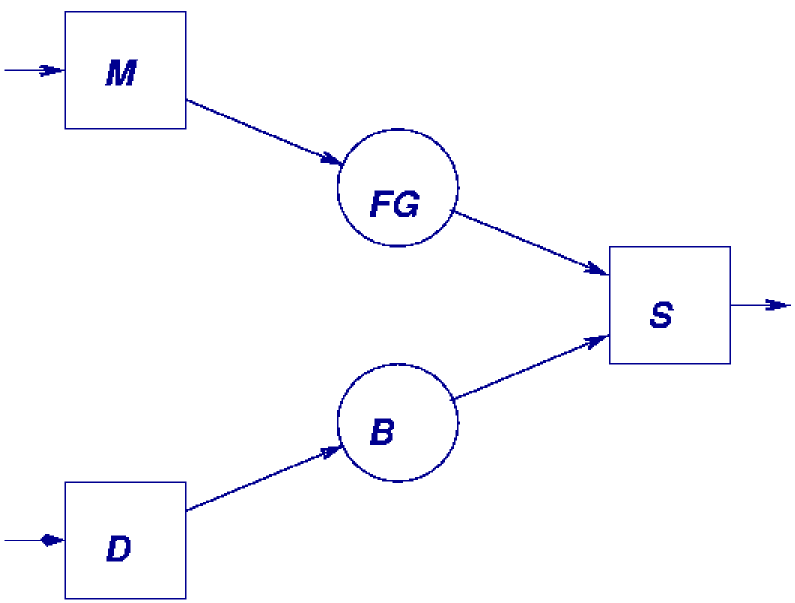
Hedging point



Simple Policies

Material/token policies

Hedging point



- Operating Machine M according to the hedging point policy is equivalent to operating this assembly system according to a finite buffer policy.

Simple Policies

- D is a *demand generator* .
  - ⋆ Whenever a demand arrives, D sends a token to B.
- S is a synchronization machine.
  - ⋆ S is perfectly reliable and infinitely fast.
- FG is a finite finished goods buffer.
- B is an infinite backlog buffer.

Simple Policies

Material/token policies

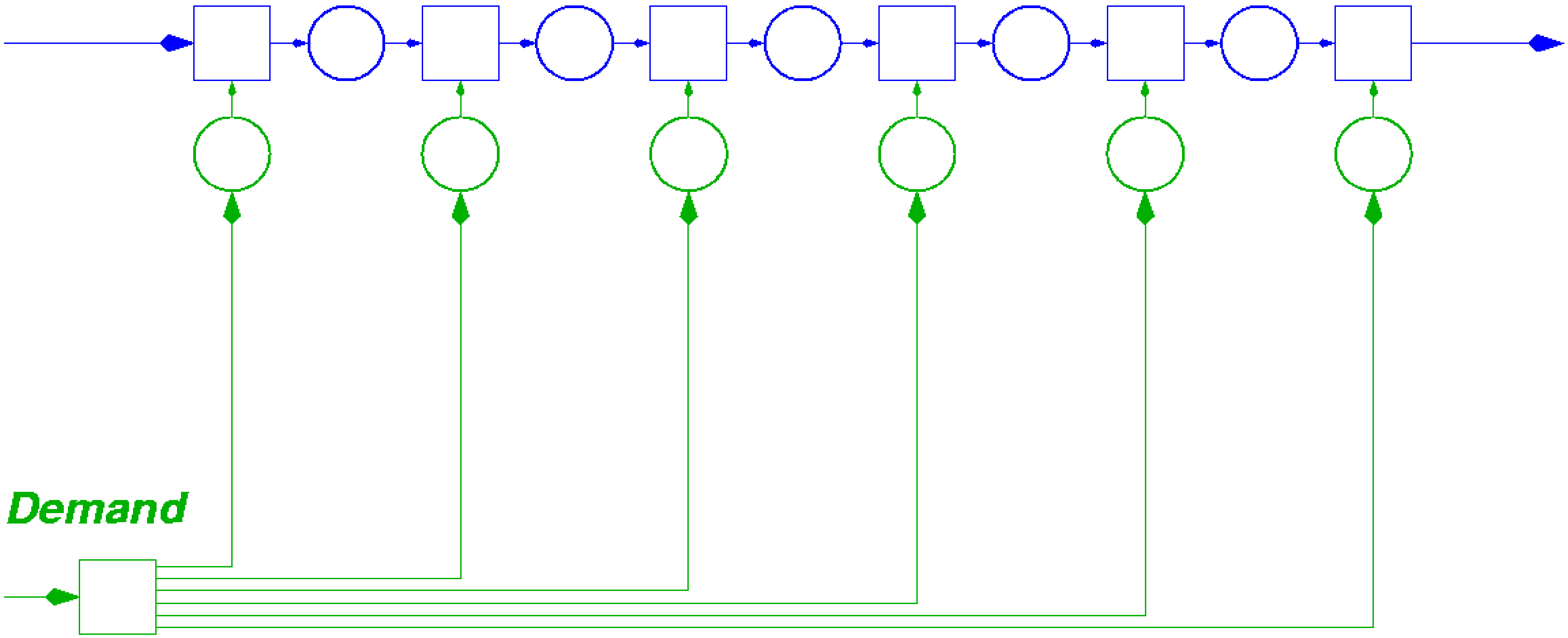
Basestock

- *Base Stock:* the amount of material and backlog between each machine and the customer is limited.
- Deviations from targets are adjusted locally.

Simple Policies

Material/token policies

Basestock Proof

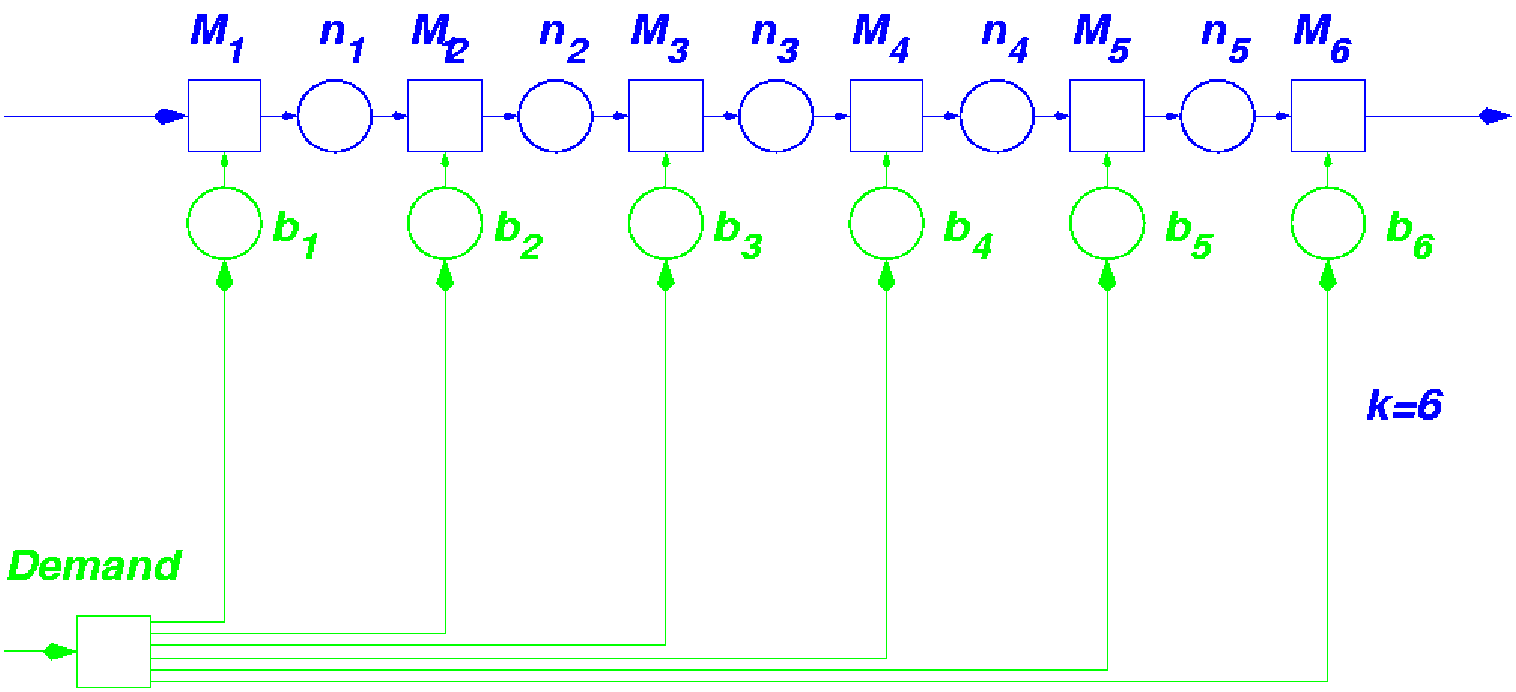


- Infinite buffers.
- Finite initial levels of material and token buffers.

Simple Policies

Material/token policies

Basestock Proof



Claim: $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k, 1 \geq j \geq k$
remains constant at all times.

Simple Policies

- Consider $b_1 + n_1 + n_2 + ... + n_{k-1} - b_k$
- When M_i does an operation $(1 < i < k)$,
  - ⋆ n_{i-1} goes down by 1, b_i goes down by 1, n_i goes up by 1, and all other b_j and n_j are unchanged.
  - ⋆ That is, $n_{i-1} + n_i$ is constant, and $b_i + n_i$ is constant.
  - ⋆ Therefore $b_1 + n_1 + n_2 + ... + n_{k-1} - b_k$ stays constant.
- When M_1 does an operation, $b_1 + n_1$ is constant.
- When M_k does an operation, $n_{i-1} - b_k$ is constant.
- Therefore, when *any* machine does an operation, $b_1 + n_1 + n_2 + ... + n_{k-1} - b_k$ remains constant.

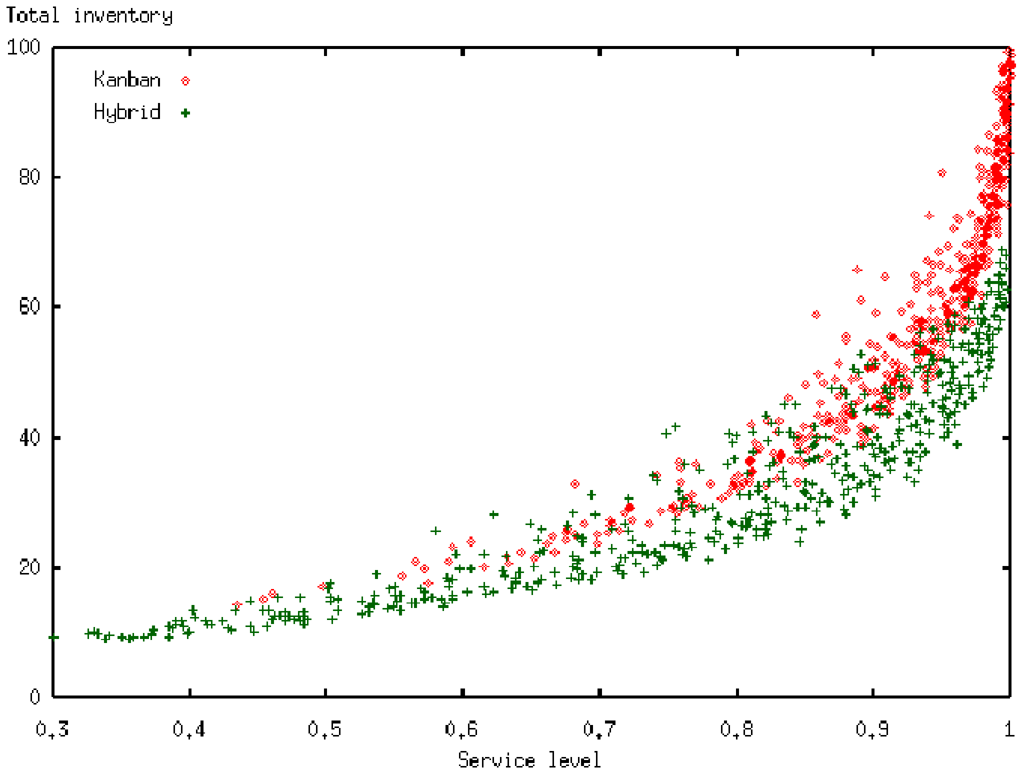
- Now consider $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k, 1 < j < k$
- When M_i does an operation, $i \geq j$, $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k$ remains constant, from the same reasoning as for $j = 1$.
- When M_i does an operation, $i < j$, $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k$ remains constant, because it is unaffected.

- When a demand arrives,
  - ⋆ n_j stays constant, for all j, and all b_j increase by one.
  - ⋆ Therefore $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k$ remains constant for all j.
- *Conclusion:* whenever *any* event occurs, $b_j + n_j + n_{j+1} + ... + n_{k-1} - b_k$ remains constant, for all j.

Simple Policies

Material/token policies

Comparisons

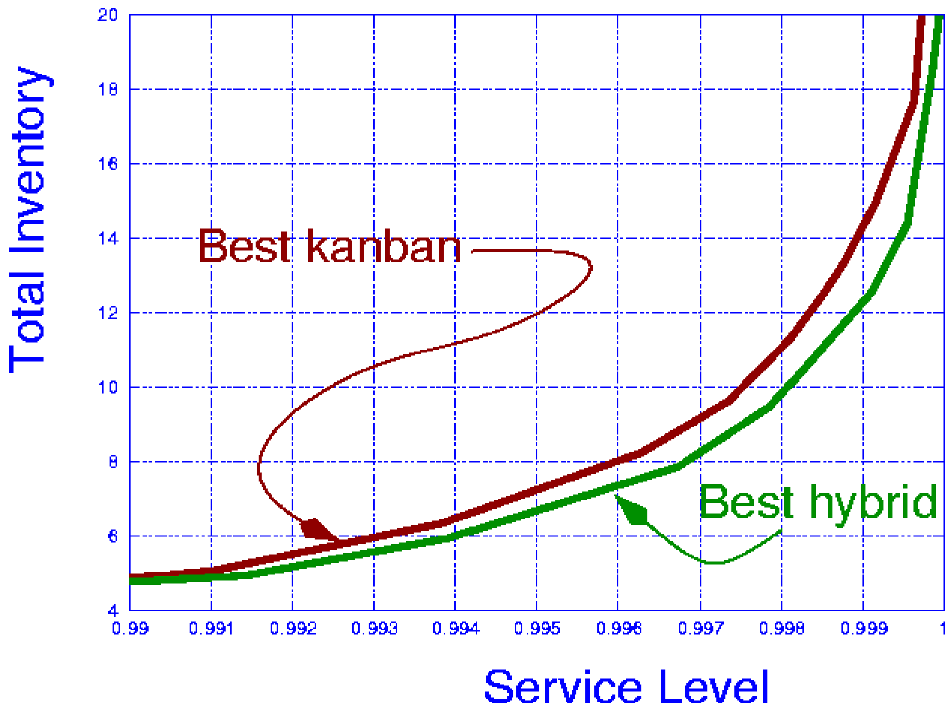


- Simulation of simple Toyota feeder line.
- We simulated *all* possible kanban policies and *all* possible kanban/CONWIP hybrids.

Simple Policies

Material/token policies

Comparisons



- The graph indicates the *best* of all kanbans and all hybrids.

More results of the comparison experiment: best parameters for service rate =.999.

Policy	Buffer sizes				Base stocks			
Finite buffer	2	2	4	10	—	—	—	—
Kanban	2	2	4	9	—	—	—	—
Basestock	∞	∞	∞	∞	1	1	1	12
CONWIP	∞	∞	∞	∞	—	—	—	15
Hybrid	2	3	5	15	—	—	—	15

More results of the comparison experiment: performance.

Policy	Service level	Inventory
Finite buffer	$0.99916 \pm .00006$	$15.82 \pm .05$
Kanban	$0.99909 \pm .00005$	$15.62 \pm .05$
Basestock	$0.99918 \pm .00006$	$14.60 \pm .02$
CONWIP	$0.99922 \pm .00005$	$14.59 \pm .02$
Hybrid	$0.99907 \pm .00007$	$13.93 \pm .03$

Simple Policies

Other policies

FIFO

- First-In, First Out.
- Simple conceptually, but you have to keep track of arrival times.
- Leaves out much important information:
  - ⋆ due date, value of part, current surplus/backlog state, etc.

Other policies

EDD

Simple Policies

- Earliest due date.
- Easy to implement.
- Does not consider work remaining on the item, value of the item, etc..

Simple Policies

Other policies

SRPT

- *Shortest Remaining Processing Time*
- Whenever there is a choice of parts, load the one with least remaining work before it is finished.
- Variations: include waiting time with the work time. Use expected time if it is random.

Simple Policies

Other policies

Critical ratio

- Widely used, but many variations. One version:
  - ⋆ Define $CR = \dfrac{\text{Processing time remaining until completion}}{\text{Due date - Current time}}$
  - ⋆ Choose the job with the highest ratio (provided it is positive).
  - ⋆ If a job is late, the ratio will be negative, or the denominator will be zero, and that job should be given highest priority.
  - ⋆ If there is more than one late job, schedule the late jobs in SRPT order.

Simple Policies

Other policies

Least Slack

- This policy considers a part's due date.
- Define *slack* = due date - remaining work time
- When there is a choice, select the part with the least slack.
- Variations involve different ways of estimating remaining time.

- Due to Eli Goldratt.
- Based on the idea that every system has a bottleneck.
- *Drum:* the common production rate that the system operates at, which is the rate of flow of the bottleneck.
- *Buffer:* DBR establishes a CONWIP policy between the entrance of the system and the bottleneck. The buffer is the CONWIP population.
- *Rope:* the limit on the difference in production between different stages in the system.
- But: What if bottleneck is not well-defined?

Conclusions

- Many policies and approaches.
- No simple statement telling which is better.
- Policies are not all well-defined in the literature or in practice.
- My opinion:
  - ⋆ This is because policies are not *derived* from first principles.
  - ⋆ Instead, they are tested and compared.
  - ⋆ Currently, we have little intuition to guide policy development and choice.