Manufacturing Systems Design and Analysis

Past Successes and Future Research

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Performance analysis of manufacturing systems

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Introduction

Summary of research in Manufacturing Systems Design and Analysis

- Motivation
  - ⋆ Economic
  - ⋆ Technical
- Specific MIT research areas
- Successes
- Current and future research

Motivation

Economic

- Frequent new product introductions.
  - ⋆ Short product lifetimes.
  - ⋆ Short process lifetimes.

This leads to frequent building, rebuilding, and reconfiguration of manufacturing systems, and this is *expensive* and *time-consuming* .

- Huge capital costs.
  - ⋆ The time required to bring factory to optimal performance is *expensive* .

Motivation

Economic

Industry Needs

- Tools to predict performance of proposed factory designs.
- Tools for optimal real-time management (control) of factories.
- Manufacturing Systems Engineering professionals who understand factories as complex systems.
  - ⋆ They must have *systems* expertise and intuition.

Motivation

Economic

Industry Needs

- These tools must be *fast* as well as accurate.
  - ⋆ Optimization for system design requires many evaluations. The more evaluations, the better the outcome can be.
  - ⋆ Real-time scheduling in response to random events must be fast. The factory cannot be idle, and should not be following an obsolete schedule, while a new one is being constructed.
- *Simulation is typically not fast enough.* We use mathematical modeling and analysis to develop our tools.

Motivation

Technical Challenges

Complexity

- Collections of things often have properties that are *unexpected* functions of the properties of the things collected.

- Some kinds of production (e.g., semiconductor fabrication) have hundreds of operations, hundreds of part types, and/or complicated material flows.

- In many practical situations, infinite buffers are not good approximations for real buffers.

Motivation

- Factories are full of random events:
  - ★ machine failures
  - ★ changes in orders
  - ★ quality failures
  - ★ human variability
- The economic environment is uncertain:
  - ★ demand variations
  - ★ supplier unreliability
  - ★ changes in costs and prices

Factories must be built and operated to minimize the damage that such phenomena can cause.

Motivation

Technical Challenges

Quantity, Quality, and Variability

- Quantity – how much and when.
- Quality – how well.

General Statement: Variability is the enemy of manufacturing.

Variability in processes reduces quality; variability in event times decreases production rates and increases inventories and lead times.

Fundamental Problems

- The first fundamental problem of manufacturing systems engineering is: *design the best possible system that meets specified requirements.*
- The second problem is: *operate a system in the best possible way to meet specified requirements.*

The criterion for “best” and the requirements are defined in terms of the performance measures and financial considerations.

Fundamental Problems

Practical Challenges

The challenge is to predict the performance measures of the system *before* it is built or operated. This is difficult because:

- Most people lack good intuition for complex systems.
- Good computational tools are challenging to develop.
- The data needed is hard to obtain.

Fundamental Problems

State of the field

- Most factories are built with simple rules by people with experience.
- Often factories are built and then modified.
- Widely-used quantitative tools are either *simple and crude*
  - ⋆ spreadsheet estimates of capacity

  or *excessively detailed*
  - ⋆ simulation or real-time scheduling optimization.

This was tolerable in the past. However, such approaches are now inadequate due to reduced factory lifetimes and intensifying global competition.

Research

Methodologies

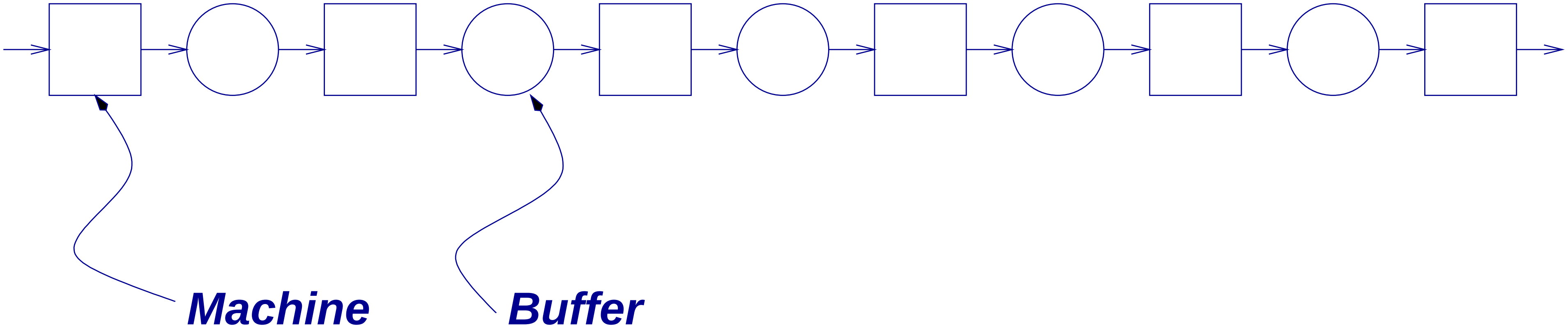
Manufacturing systems research is concerned with the modeling of systems for the purpose of computing quantity- and quality-related performance measures. It makes heavy use of

- stochastic processes,
- approximation methods,
- nonlinear analysis and optimization,
- statistics,
- and other mathematical fields.

Earlier Research

Flow Line

... or *Flow shop* , *Transfer line* , or *Production line.*



Traditionally used for high volume, low variety production.

Earlier Research

Flow Line

Reference

Manufacturing Systems Engineering

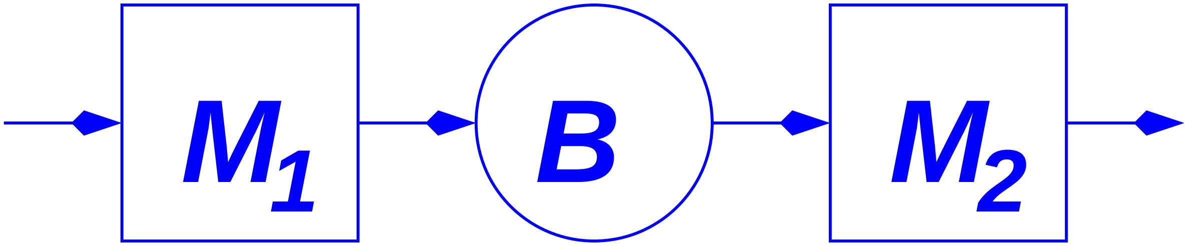
by Stanley B. Gershwin

`http://home.comcast.net/~hierarchy/MSE/mse.html`

Earlier Research

Flow Line

Two-Machine Line



- The machines are unreliable — they fail at random times and are repaired at random times.
- As a consequence, machines cause each other to be forced idle at random times for random durations. This reduces production.
- Goal of analysis: calculate production rate, in-process inventory.

Earlier Research

Flow Line

Two-Machine Line

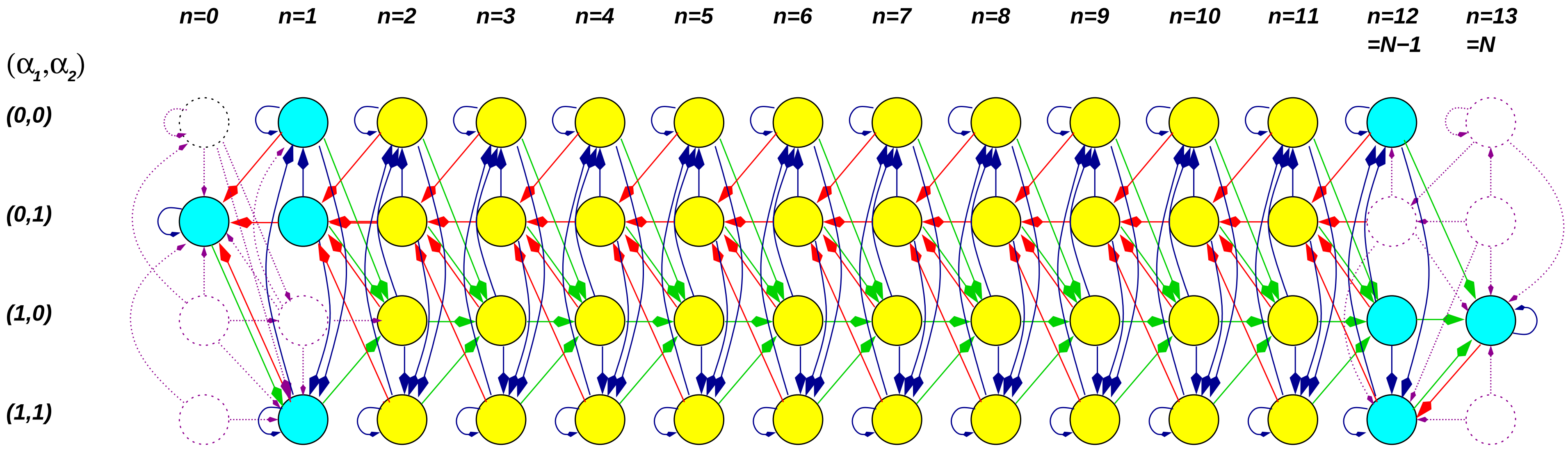
Method of analysis:

1. Construct Markov chain model.
2. Determine steady-state probability distribution.
3. Calculate average production rate and average inventory from steady-state probability distribution.

Earlier Research

Flow Line

Two-Machine Line



key

states

transient ◌

non−transient

boundary ●

internal ●

transitions

out of transient states ⇢

out of non−transient states

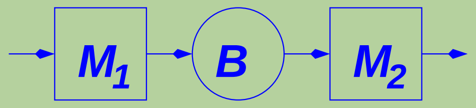
to increasing buffer level →

to decreasing buffer level →

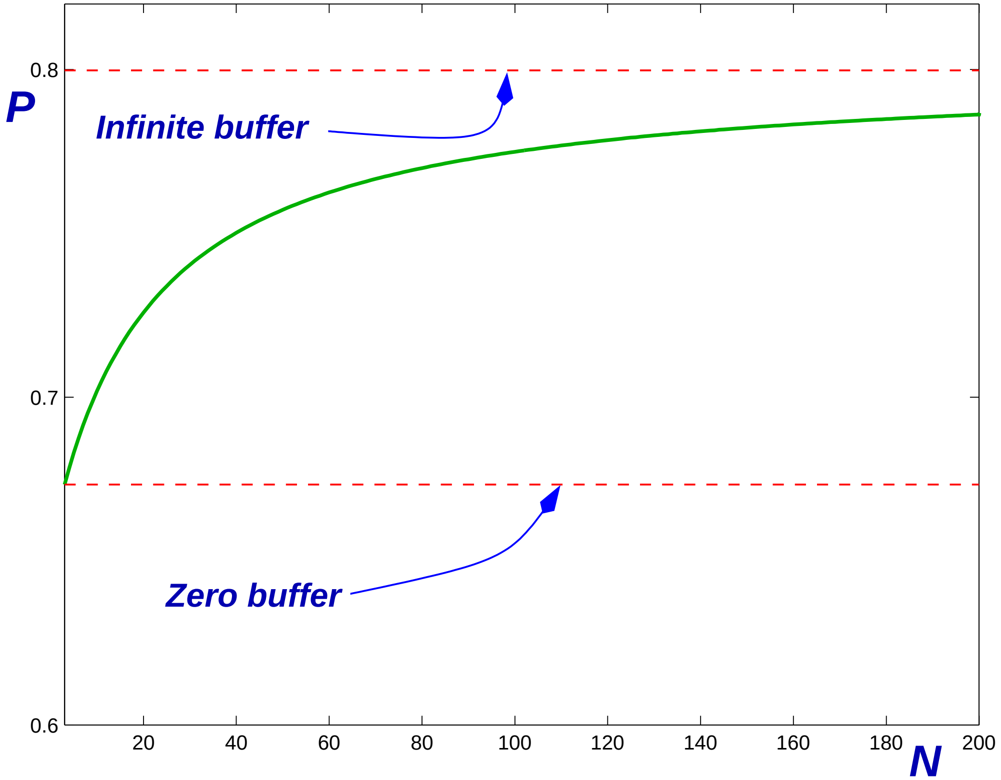
unchanging buffer level →

Earlier Research

Quantity



- We vary the buffer size N and observe its effect on the production rate P.
- *Observation:* the production rate increases monotonically up to a limit.
- However, increasing N increases inventory and other costs.



Note: The upper limit is what would be estimated by a simple capacity formula.

Earlier Research

Quantity

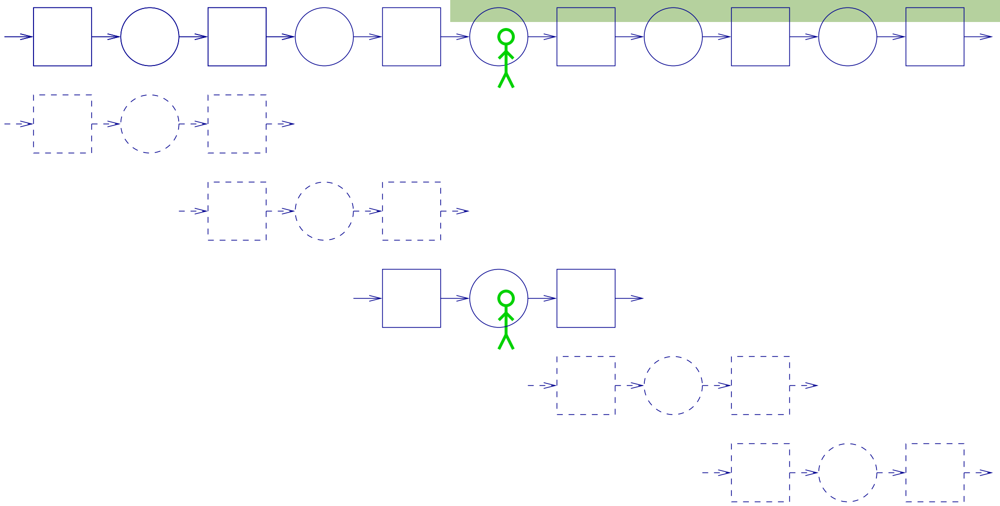
Long Lines

- Problem: Longer lines have larger state spaces. The state space grows *exponentially* in the length of the line.
- Dealing with large state spaces is the *fundamental technical problem* of manufacturing systems analysis.
- Solution: Approximate one long line by many small lines.

Earlier Research

Decomposition

Long Lines



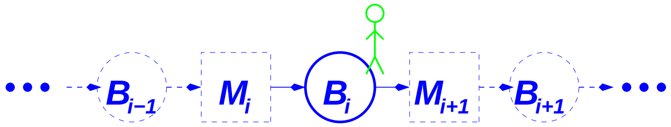
- Decomposition breaks up systems and then reunites them.
- Conceptually: put an observer in a buffer, and tell him that he is in the buffer of a two-machine line.
- Question: *What would the observer see, and how can he be convinced he is in a two-machine line? Construct the two-machine line. Construct all the two-machine lines.*

Earlier Research

Decomposition

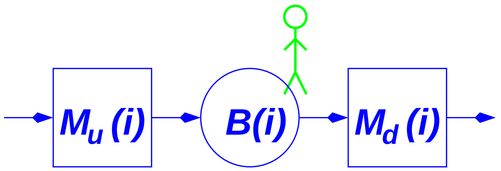
Long Lines

- Consider an observer in Buffer B_i.



  - ⋆ Imagine the material flow process that the observer sees *entering* and the material flow process that the observer sees *leaving* the buffer.

- We construct a two-machine line $L(i)$
  - ⋆ ie, we find machines $M_u(i)$ and $M_d(i)$



  such that an observer in its buffer will see almost the same processes.

- The parameters are chosen as functions of the parameters of the long line and of the parameters of the *other* two-machine lines.

Earlier Research

Decomposition

Long Lines

- The number of equations is now *linear* in the length of the line.
- An iterative algorithm works well.
- Results have been extensively compared with simulation, and they are very accurate.

Earlier Research

Successes

- A Hewlett Packard ink jet printer factory was built using MIT techniques. The estimated economic impact was hundreds of millions of US dollars.
- General Motors has used similar tools and claims a savings of two billion US dollars.
- Peugeot is also using, and further developing, such methods for designing automobile factories.
- These tools have also been used in frozen food and medical device production.

Earlier Research

Decomposition

Extensions

- *Optimization:* evaluation embedded in gradient search.
  - ⋆ *Primal* Minimize buffer space subject to production rate constraint.
  - ⋆ *Dual* Maximize production rate subject to buffer space constraint.
- Acyclic A/D (tree-structured) systems
- Single- and multiple-loop systems
  - ⋆ Pallets and kanbans

Example

- Design the buffers for a 20-machine production line.
- The machines have been selected, and the only decision remaining is the amount of space to allocate for in-process inventory.
- *The goal is to determine the smallest amount of in-process inventory space so that the line meets a production rate target.*

Example

- The common operation time is one operation per minute.
- The target production rate is .88 parts per minute.

Machine Reliability Parameters					
Case	MTTF	MTTR	MTTF	MTTR	P_∞, parts/min
	Most machines, min		Machine 5, min		
1	200	10.5	200	10.5	.95
2	200	10.5	100	10.5	.905
3	200	10.5	200	21	.905

Example

First question: are buffers really needed?

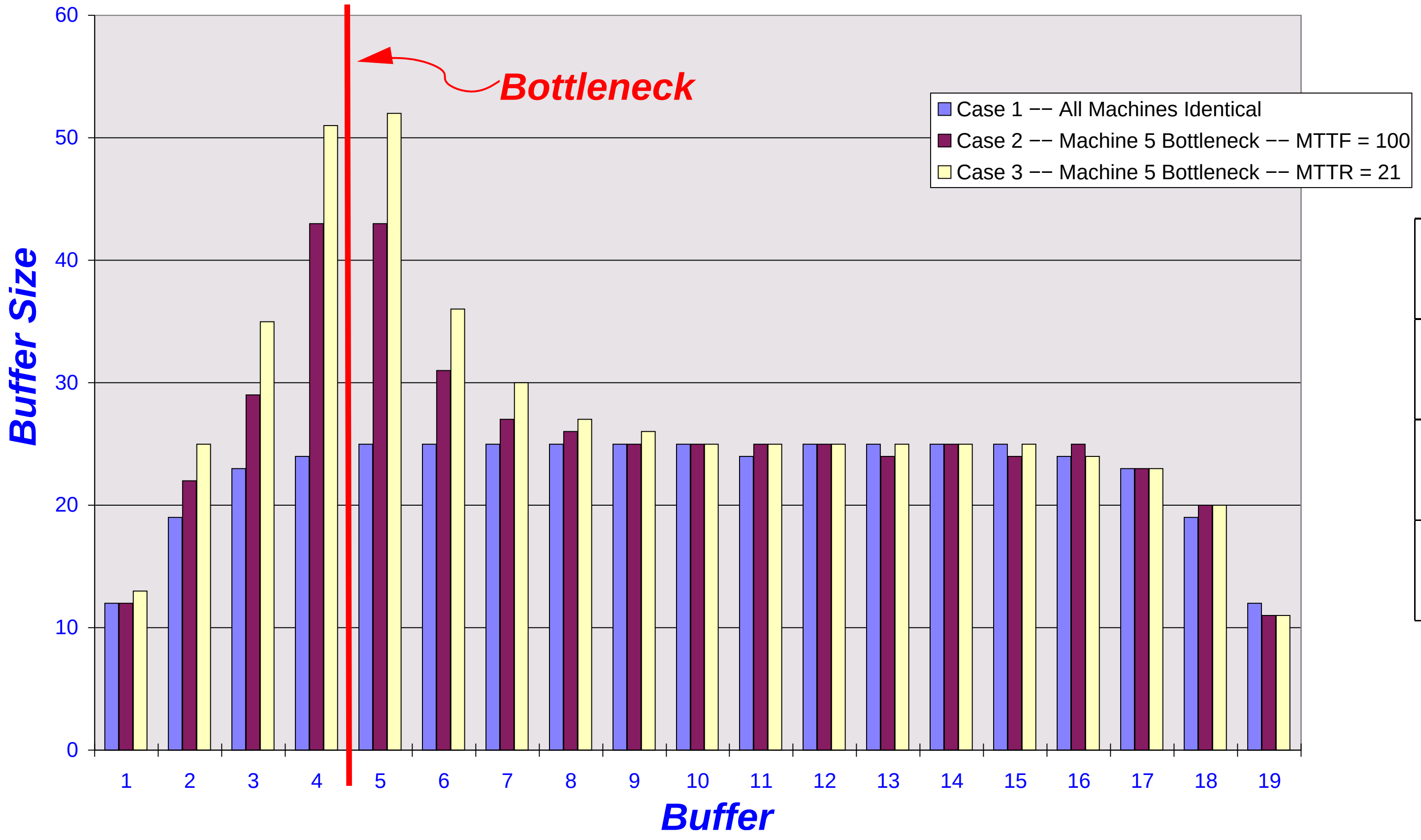
Line	Production rate with no buffers, parts per minute
Case 1	.487
Case 2	.475
Case 3	.475

Yes.

Example

Optimal buffer space distribution

Solution



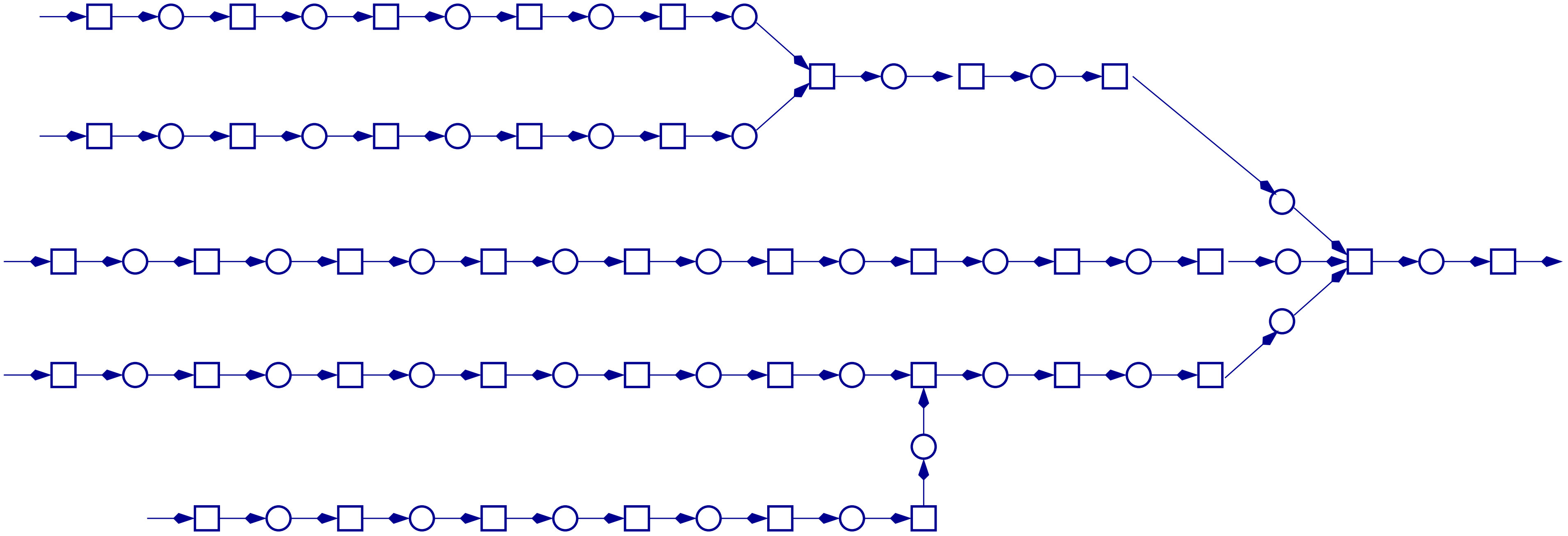
Line	Space
Case 1	430
Case 2	485
Case 3	523

Example

- Observation from studying buffer space allocation problems:
  - ⋆ *Buffer space is needed most where buffer level variability is greatest!*

Earlier Research

Acyclic A/D

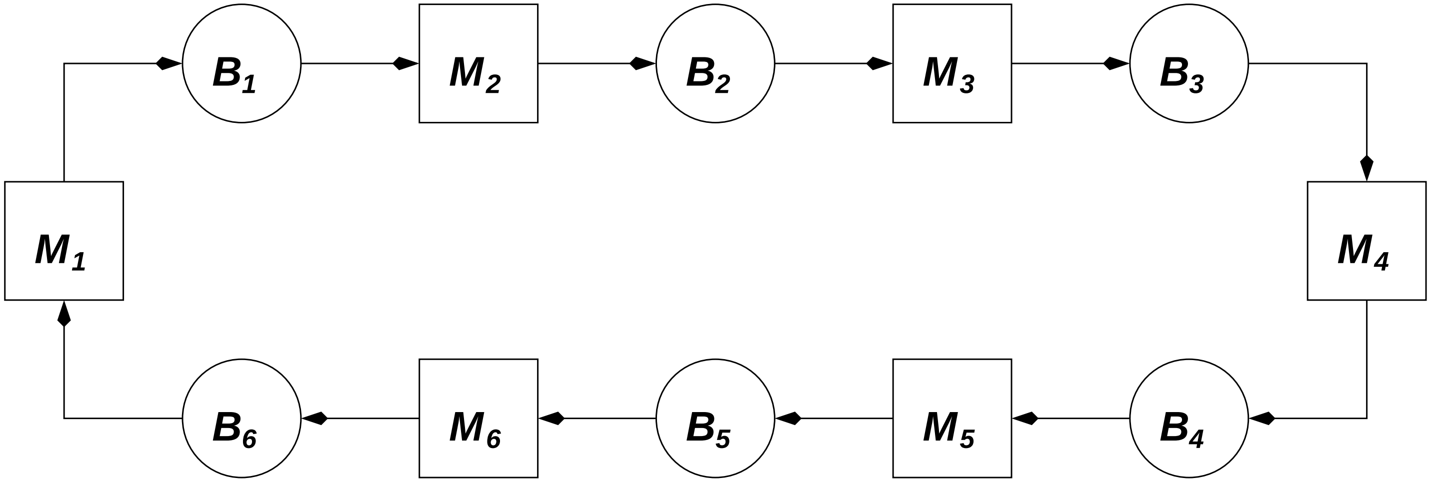


Acyclic A/D (tree-structured) systems

- Straightforward extension of line equations and algorithm

Earlier Research

Single-loop systems



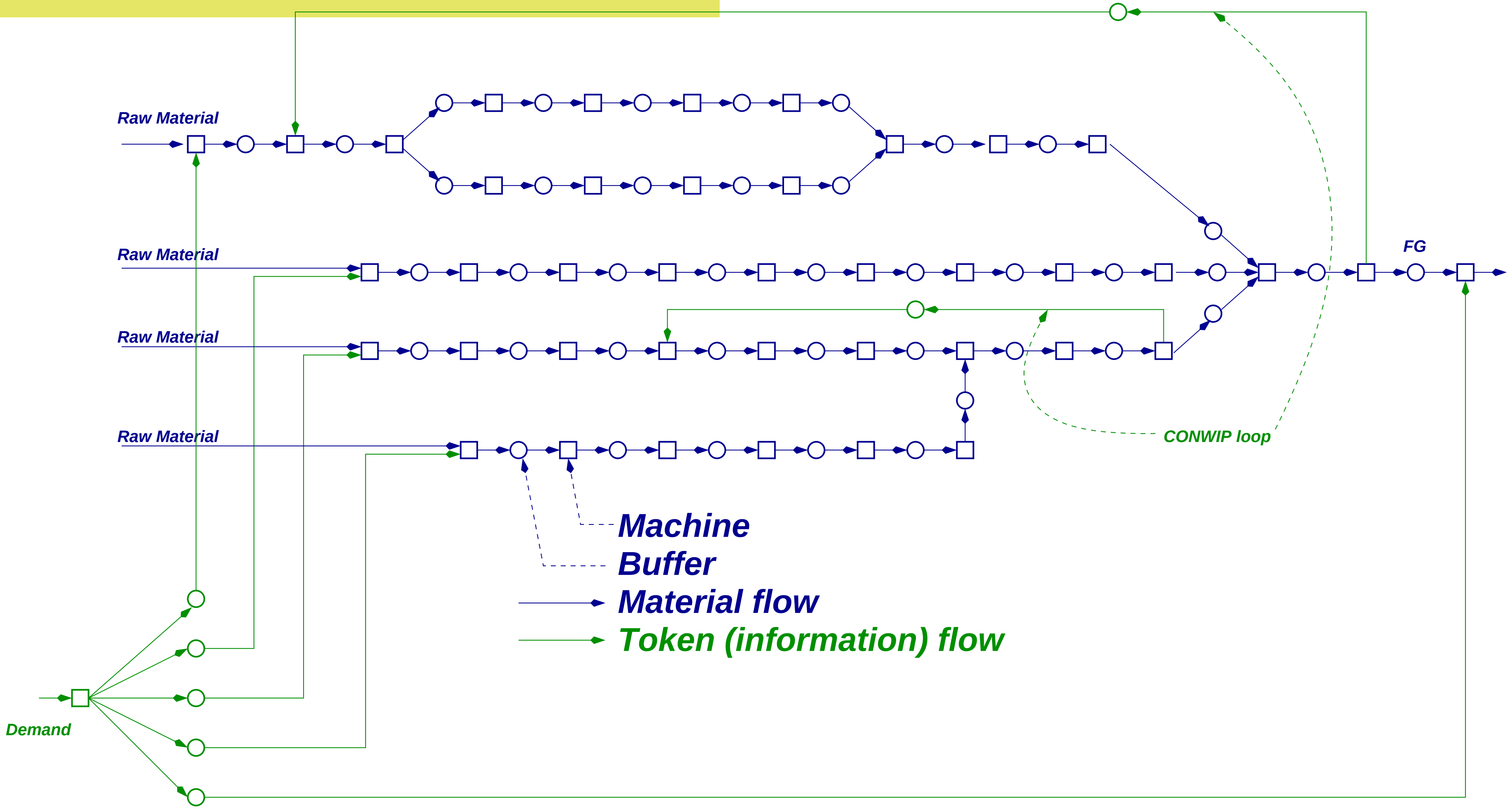
- Finite buffers $(0 \leq n_i(t) \leq N_i)$.
- Fixed population *invariant:* $\sum_i n_i(t) = N$.
- Motivation:
  - ⋆ Limited pallets/fixtures.
  - ⋆ CONWIP (or hybrid) flow control.

Earlier Research

- The invariant creates complications for the decomposition.
- Multiple-loop systems have one invariant per loop.
- More loops create more opportunities for control.

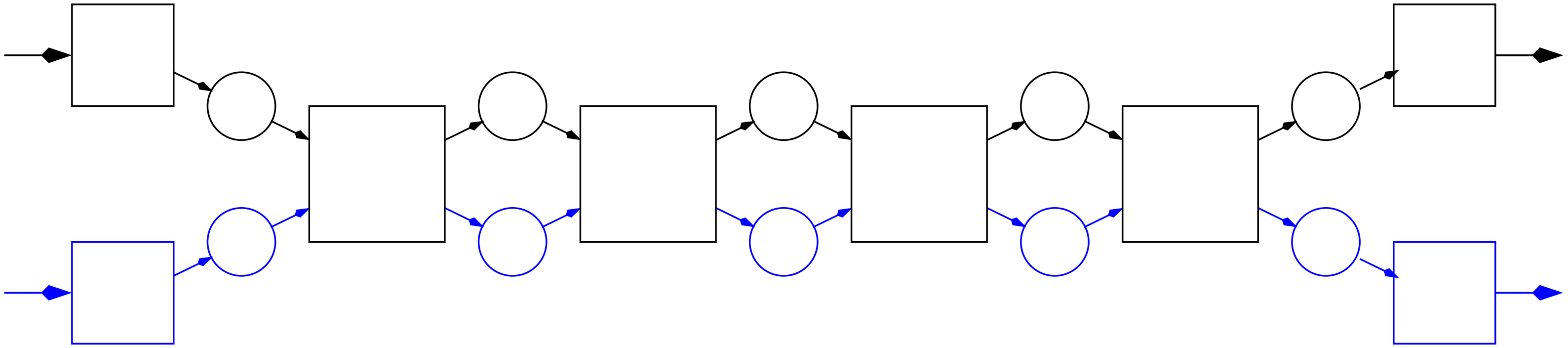
Earlier Research

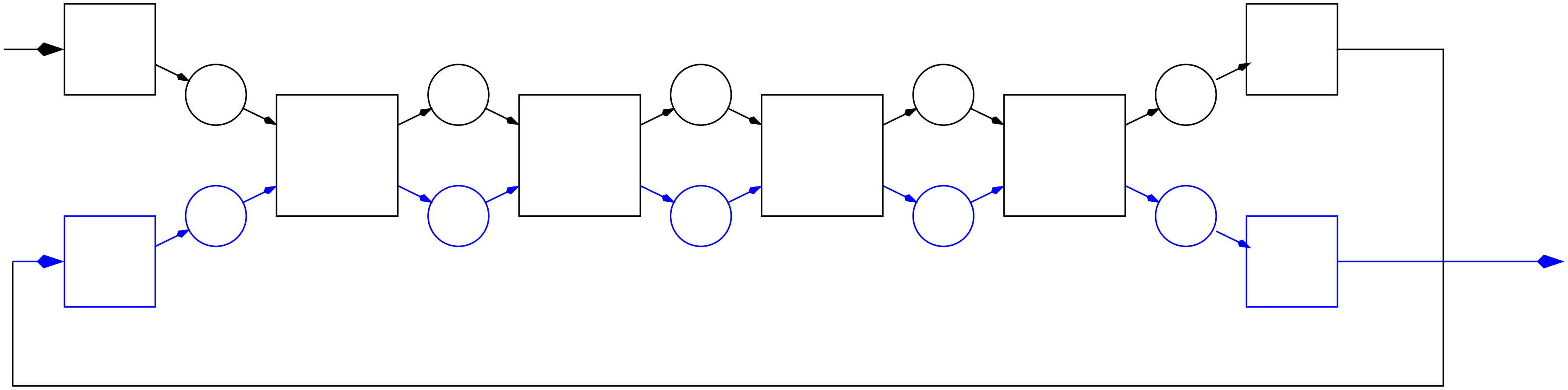
Loops



Current Research

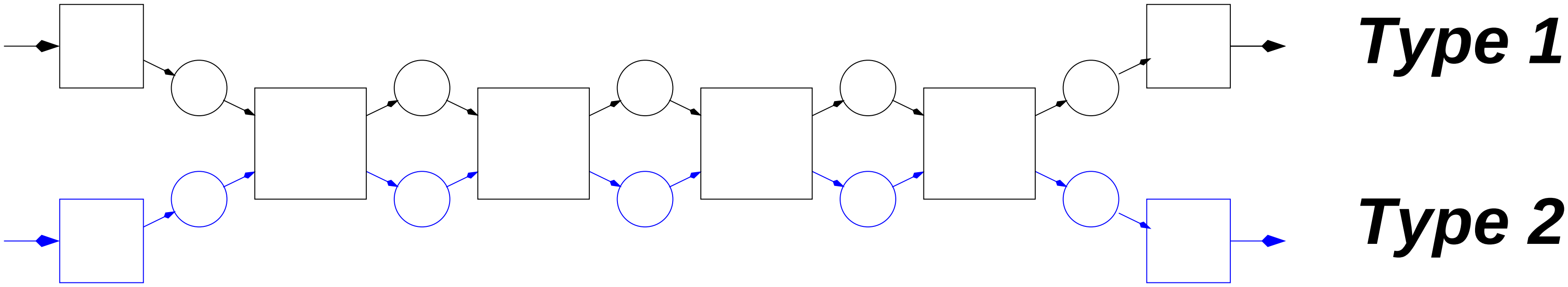
Multiple part types and reentrant flow

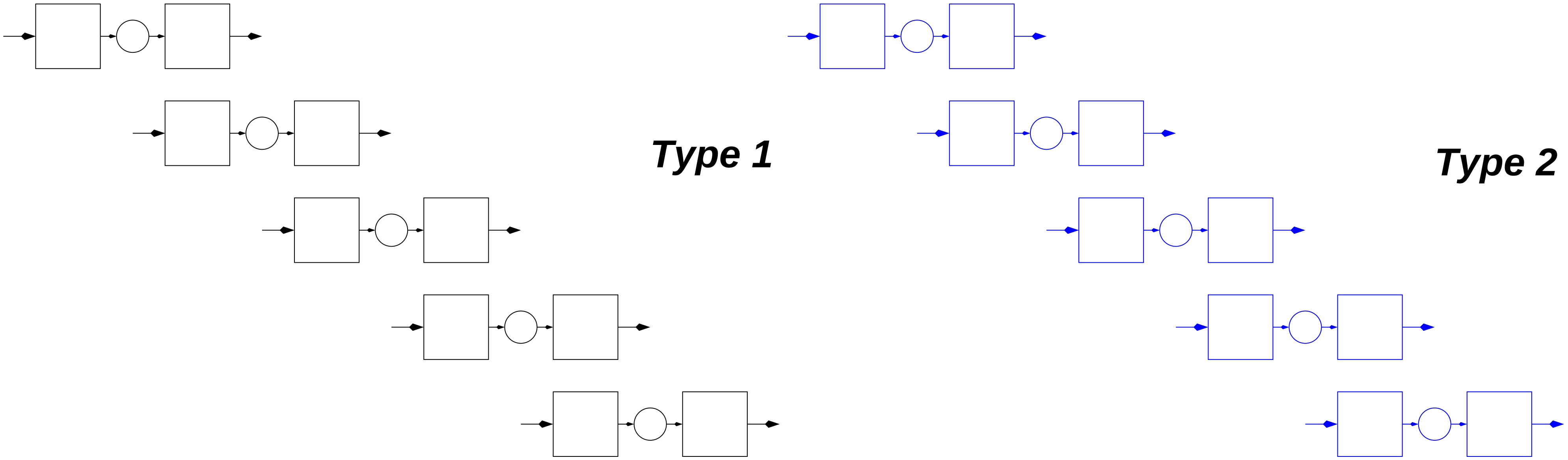




Current Research

Multiple part types and reentrant flow





Current Research

Multiple part types and reentrant flow

- We assume strict priority.
  - ⋆ This assumption will be extended.
- Two-part type decomposition has been done.
  - ⋆ Extension to three part types is next;
  - ⋆ extension to more than three should be easy.
- Reentrant flow is modeled as an extension to multiple-part types.
  - ⋆ Part reenters system as a new part type.
  - ⋆ Parts with fewer remaining operations can be given priority.

Current Research

Quality/Quantity Modeling

Quality Dynamics

- *Definition:* How the quality of a machine changes over time.
- The quality literature distinguishes between *common causes* and *special causes* . (Other terms are also used.)
  - ⋆ Common cause: successive failures are equally likely, regardless of past history.

    `GGGGBGGGBGGGGGGBGGBGGGBBGGGGGGG.....`
  - ⋆ Special cause: something happens to the machine, and failures become much more likely.

    `GGGBGGGGBGGGGGGBBBBBBGBBBBGBBGB.....`
- We use this concept to extend quantity models.

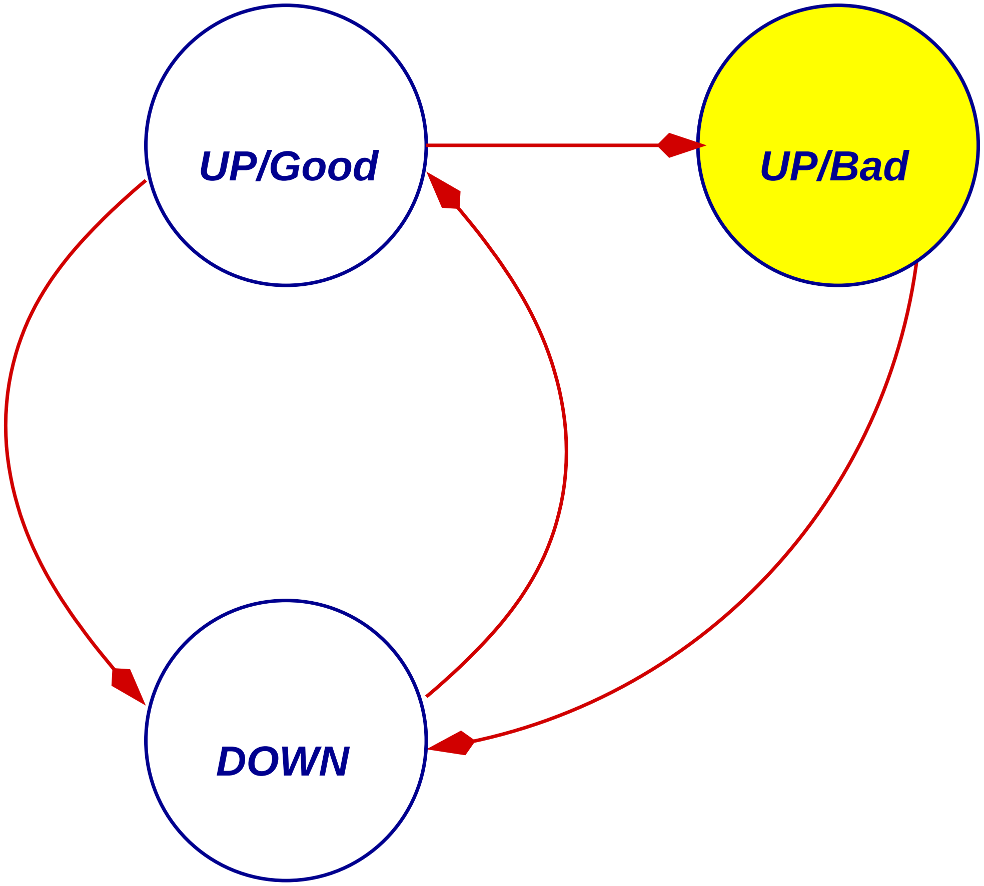
Current Research

Quality/Quantity Modeling

Simplest model

Versions:

- The *Good* state has 100% yield and the *Bad* state has 0% yield.
- The *Good* state has high yield and the *Bad* state has low yield.

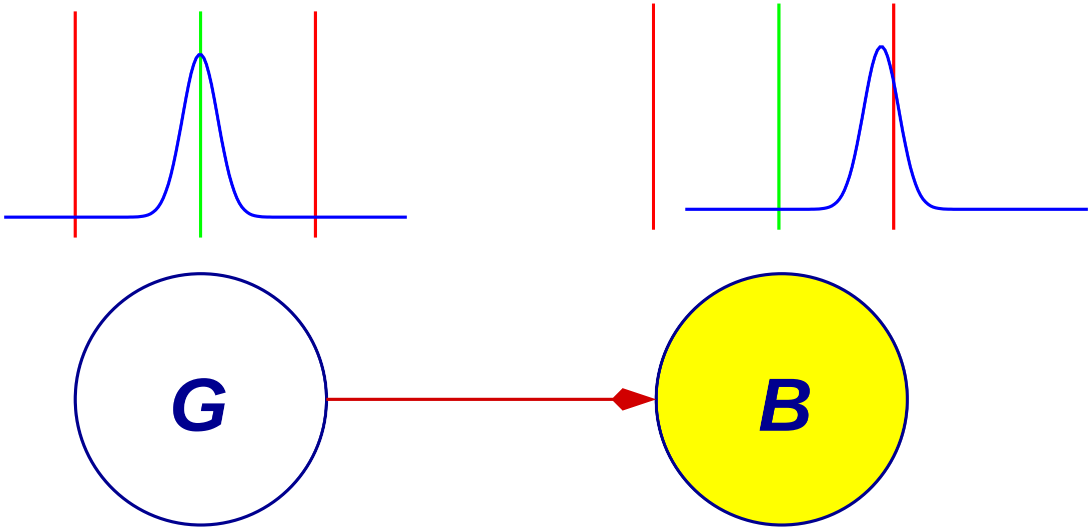


Current Research

Quality/Quantity Modeling

Simplest model

The relationship between quality dynamics and statistical process control:

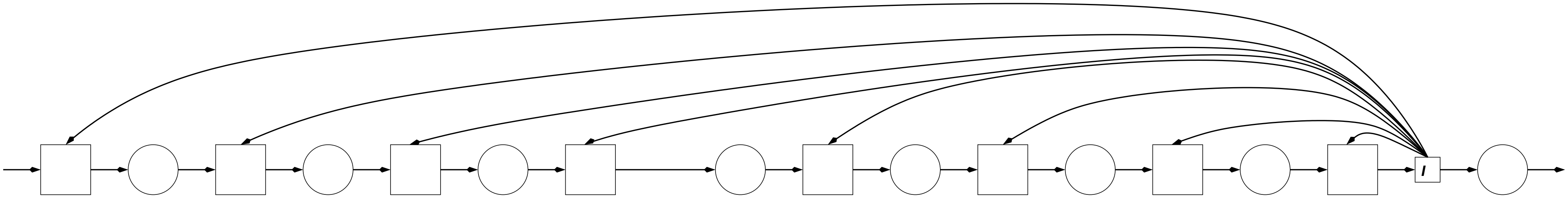


Note: The operator does not know when the machine is in the bad state until it has been detected.

Current Research

Quality/Quantity Modeling

Inspection in long lines



- The transition from UP/BAD to DOWN is signaled from a downstream inspection.
- The detection of the failure can only occur when the *first bad part* reaches the inspection station.
- Thus the production rate of *good* parts depends on how much inventory there is between the machine and the inspection.

Current Research

Quality/Quantity Modeling

Inspection in long lines

To analyze this system by decomposition, we must

- analyze two-machine lines with multiple up- and down-states, and
- relate the transition rate from UP/BAD to DOWN to the amount of inventory between the operation and the inspection.

Current Research

Quality/Quantity Modeling

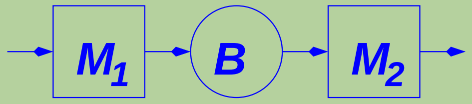
Separation of Operation and Inspection

Opinions:

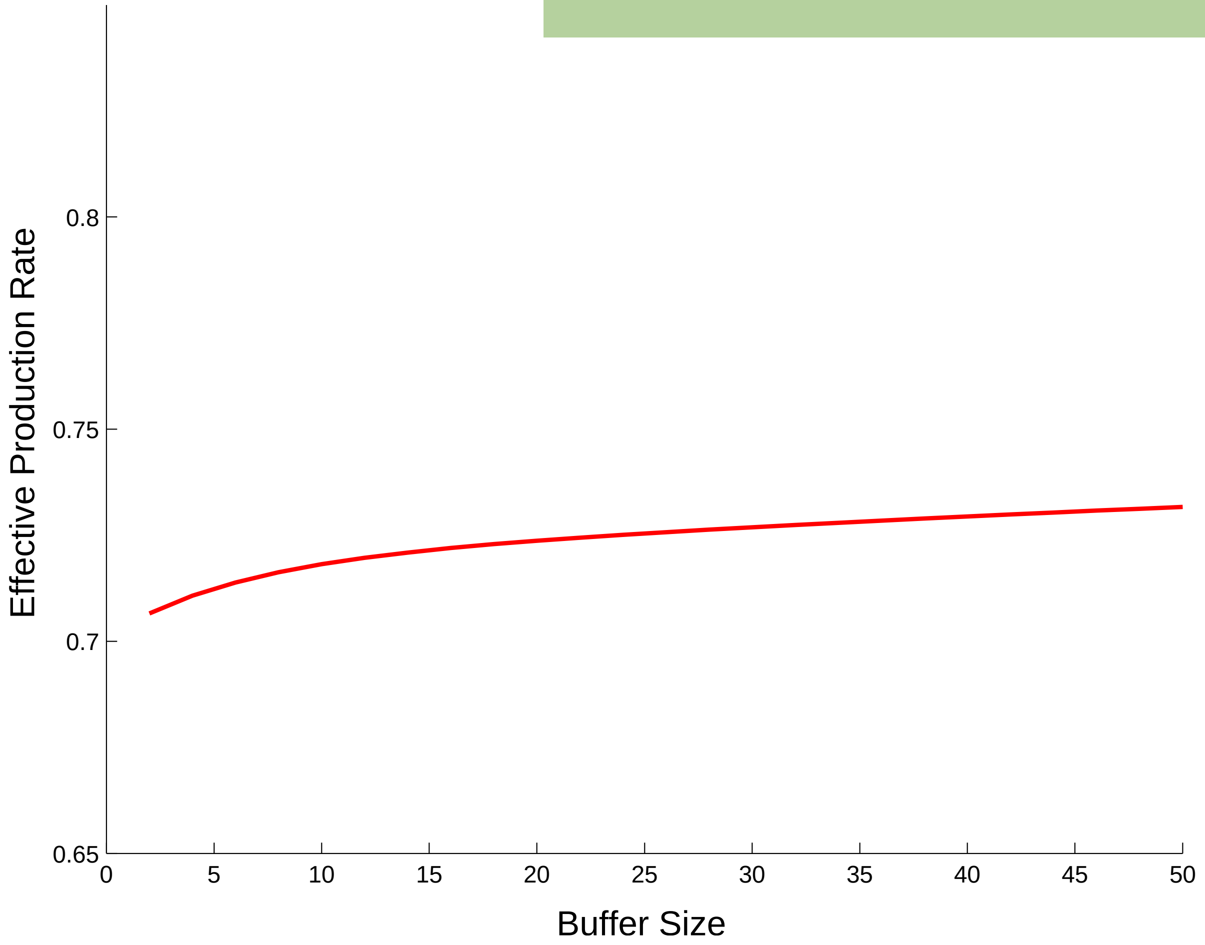
- Quantity-oriented people tend to assume that increasing a buffer *increases* the production rate.
- Quality-oriented people tend to assume that increasing a buffer *decreases* the production rate of good items.
- However, we have found that the picture is not so simple.

Current Research

Quality/Quantity Modeling



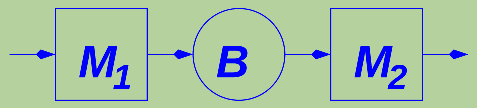
Beneficial Buffer



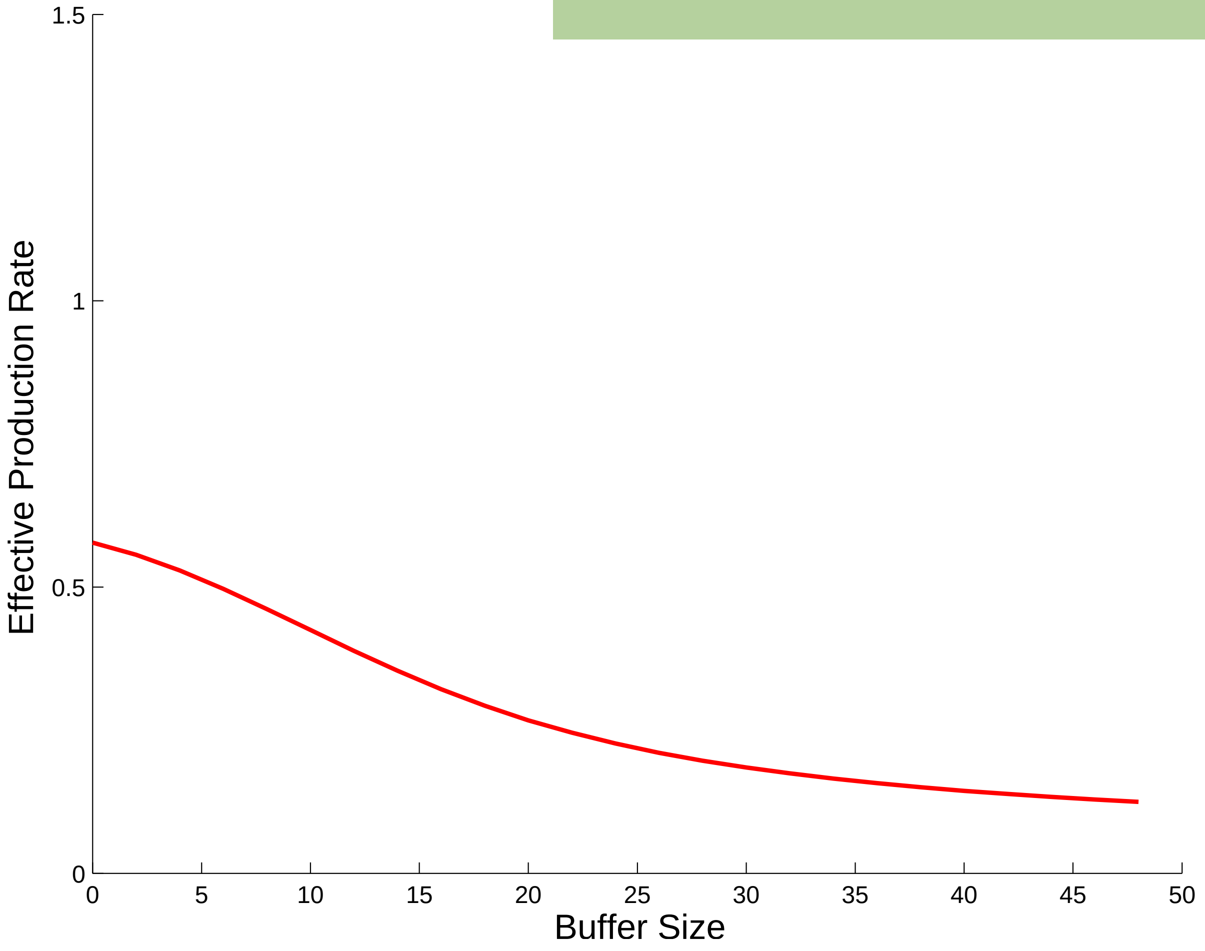
Effective production rate = production rate of good parts.

Current Research

Quality/Quantity Modeling

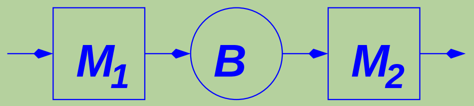


Harmful Buffer

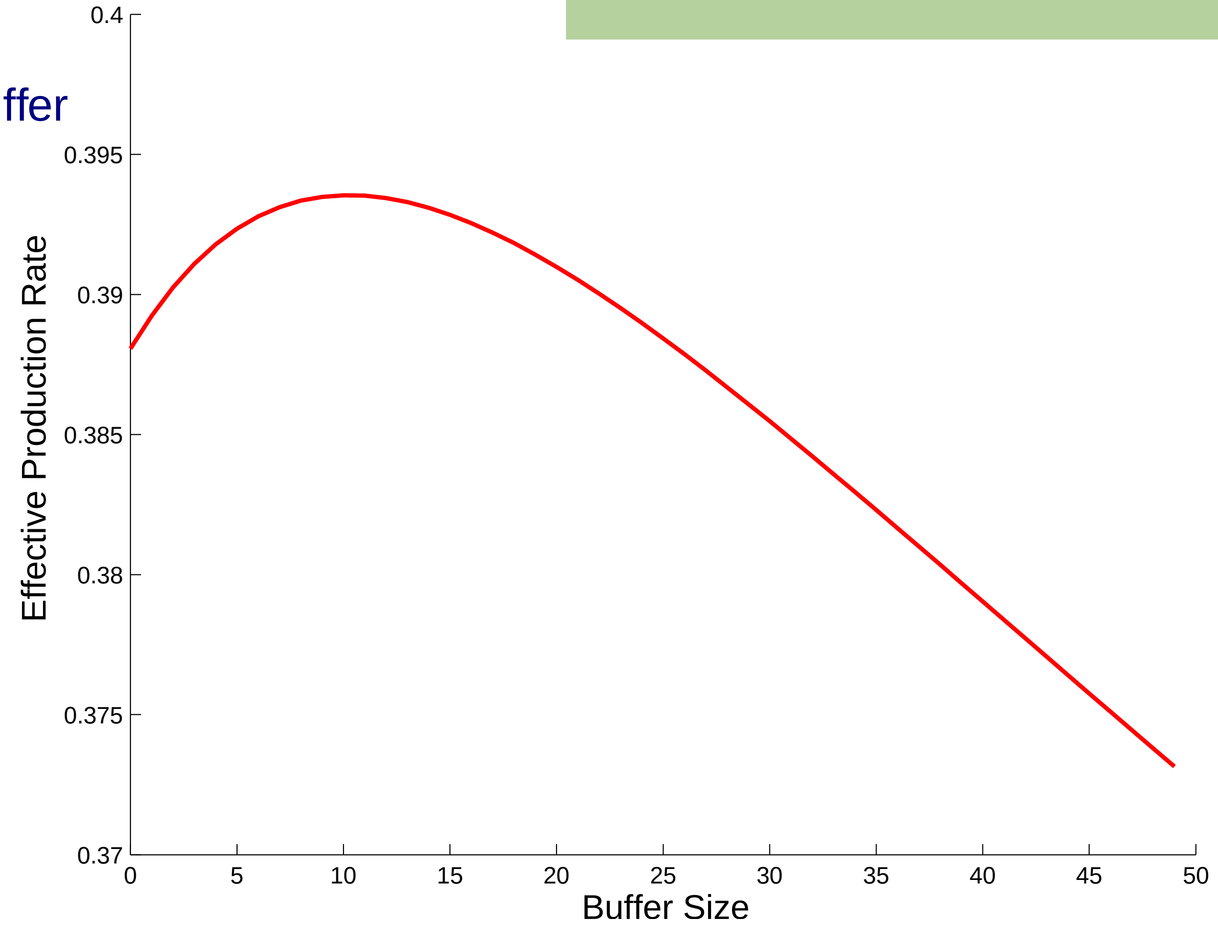


Current Research

Quality/Quantity Modeling



Mixed-Benefit Buffer



Current Research

Quality/Quantity Modeling

Inspections

How many inspections should there be? And where?

- Intuition: more inspection improves quality.
- Reality: increasing inspection can actually reduce quality, if it is not done well.

Current Research

Quality/Quantity Modeling

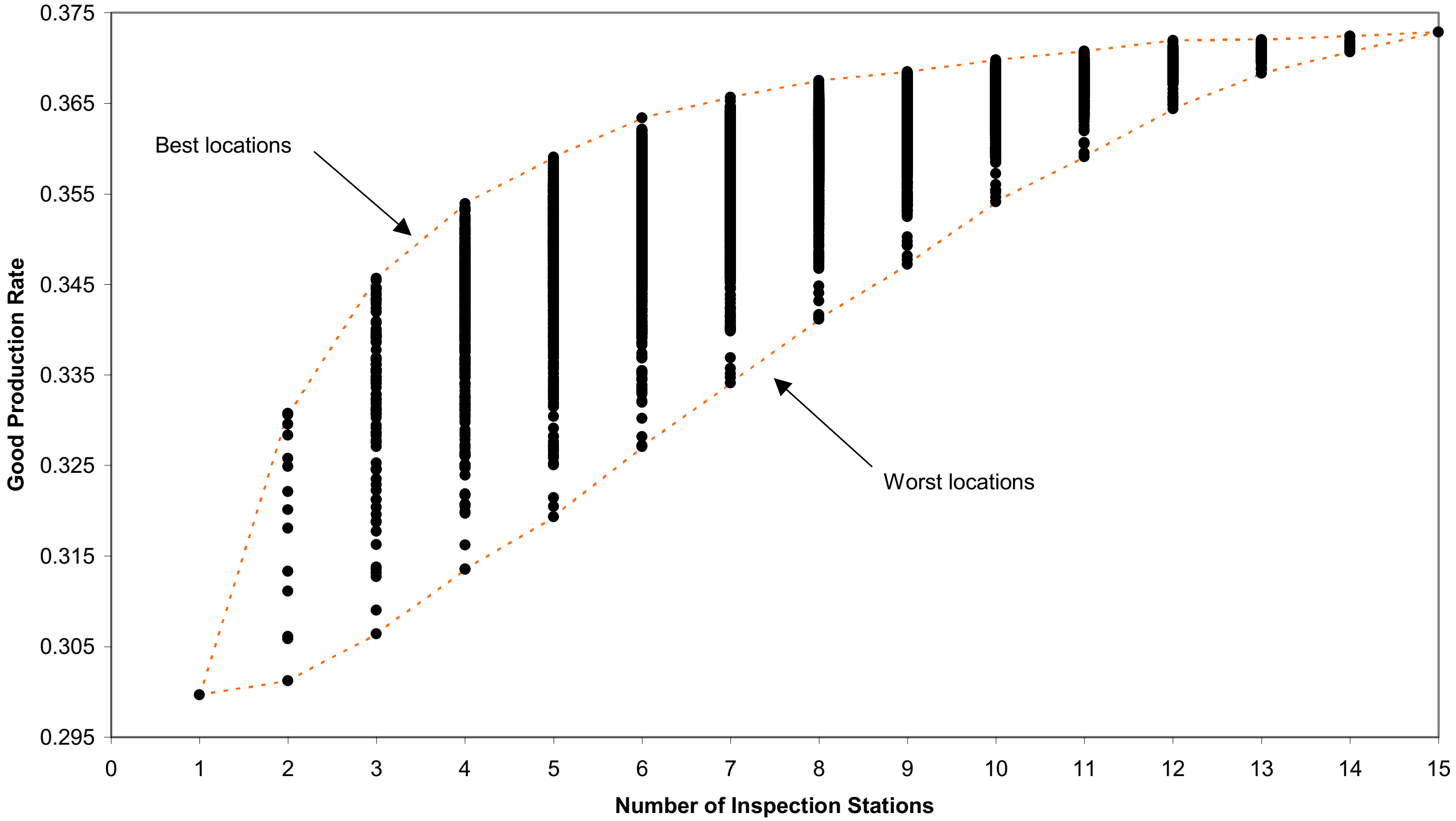
Inspections

- We simulated a 15-machine, 14-buffer line.
- All machines and buffers were identical.
- We looked at all possible combinations of inspection stations in which all operations were inspected.
  - ⋆ *Example:* Inspection stations just after Machines 6, 9, 13, and 15.
  - ⋆ The first inspection looks at the results from Machines 1 – 6; the second looks at results from Machines 7 – 9; the third from 10 – 13; and the last from 14 and 15.
  - ⋆ There is always one inspection after Machine 15.
- A total of 2^{14}=16,384 cases were simulated.

Current Research

Quality/Quantity Modeling

Inspections



Current Research

Quality/Quantity Modeling

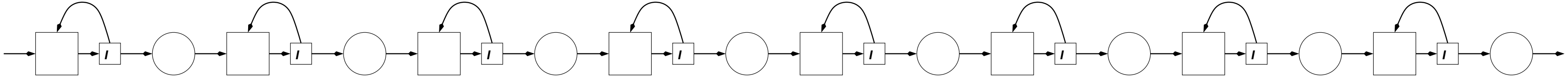
Possible Extensions

- Design of inspection policies using Bayesian analysis.
- Analysis of multiple-state machines.
- Analysis of lines with multiple-state machines.
- Control of material flow in systems with quality issues.

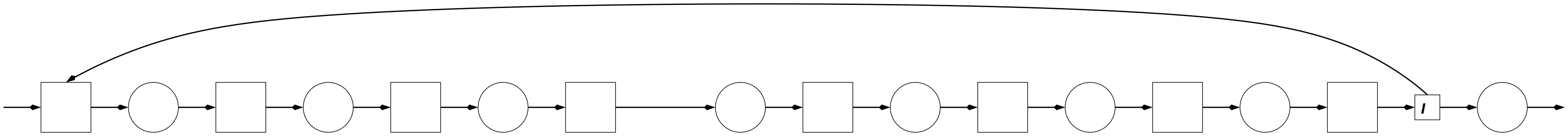
Current Research

Analytic evaluation of long lines

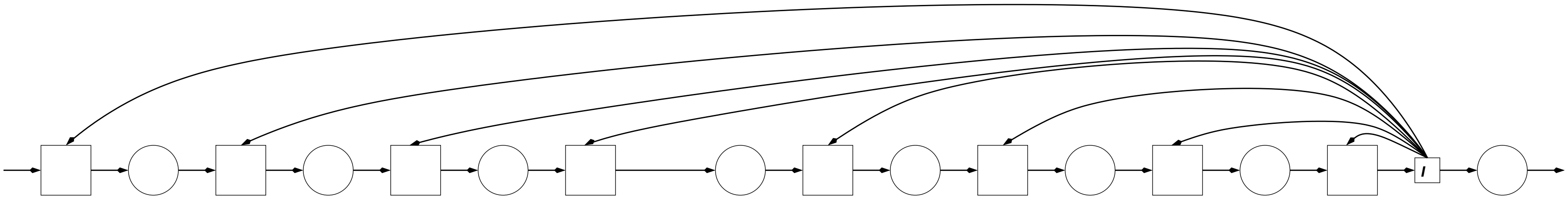
Ubiquitous inspection:



Single remote inspection of a single machine:



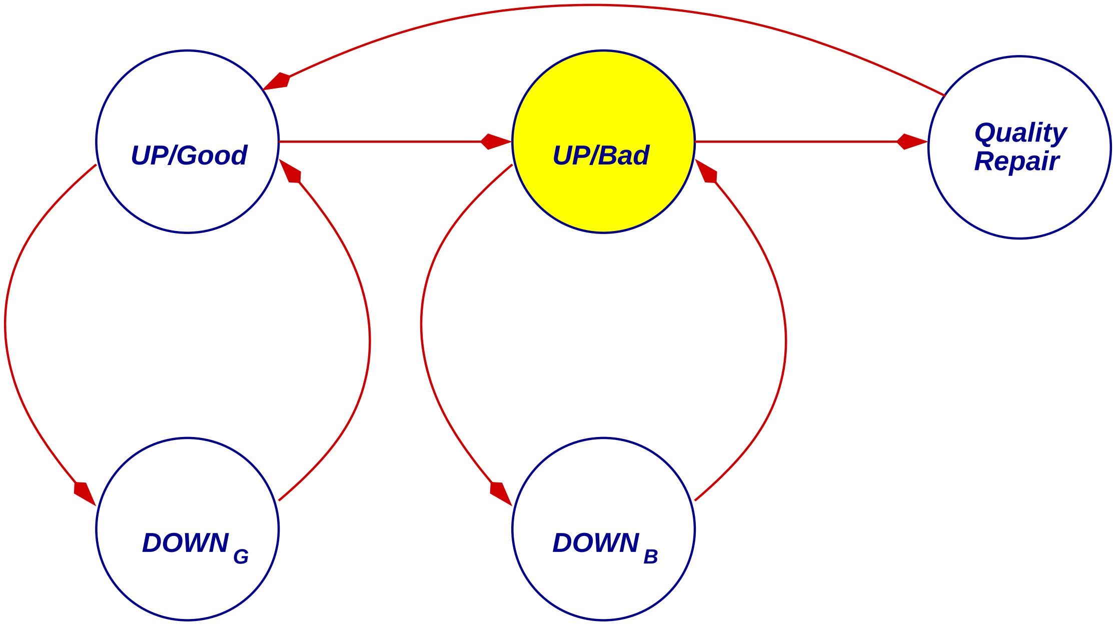
Single remote inspection of multiple machines:



Current Research

Machine quality dynamics

- The three-state machine model is much too simple.
- One extension is

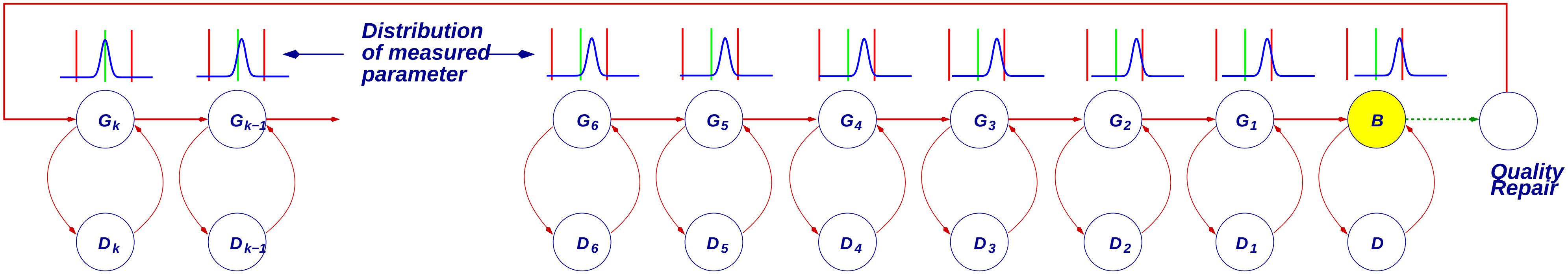


- ... but even this leaves out important features.

Current Research

Machine quality dynamics

- Another extension is



- This allows more general wear or aging models.

Conclusions

- Manufacturing systems engineering is valuable economically and intellectually.
- There are many interesting and important untreated problem areas.