An Overview of Recent Research in Design and Operation of Manufacturing Systems

by

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Outline

- Introduction
- Design
- Operation
- Heuristics
- Dynamic Programming
- Single Station
- Networks
- Hierarchy
- New Directions

Introduction

- Two major issues: design and operation
- Performance measures:
  - Capital cost
  - Production Rate or Capacity
  - Cycle Time
    the time a part spends in the system
  - Lead Time
    the time between order and delivery
  - Machine Utilization
  - Work in Process (WIP)
  - On-time Performance

Design

- Jackson-type networks:
  - infinite buffers
  - exact decomposition
  - CANQ by Solberg
  - FMS, multiple part types.
- Flow lines or transfer lines
  - exact results for 0-buffer lines, infinite buffer lines, two-machine lines.
  - approximate decomposition results for long lines with finite buffers.
  - Single part types.
  - Extended to tree-structured (acyclic) assembly/disassembly systems.
  - Finite buffers important to limit inventory – propogation of disruptions upstream.

Current work:

- loop networks
- optimization
- multiple machines per station
- variability of output

Difficulty with Loops

- **Correlation:** the total number of parts in the system is fixed. If a part is known to be at a certain location, there are fewer parts for all the other locations.

- However, this appears NOT to be a problem if the loop is sufficiently large.

- What will happen when there are multiple loops?

Operation

- We focus on real-time scheduling.
- Scheduling is the selection of times for future controllable events.
- Scheduling calculations must be fast to be useful in real time.

Heuristic approaches

- FIFO,
- SRPT
- kanban
- CONWIP
- LS
- many others

important distinction: LS keeps track of when parts are due.

- advantage: easy to implement
- disadvantage: hard to determine if or why policies are good

Dynamic programming approaches

- advantage: optimal
- disadvantages:
  - impossible to determine exactly except for trivial problems;
  - difficult to implement optimal even if we could get it;
  - no bounds for approximations;
  - most people believe that optimal is not much better than good heuristic.

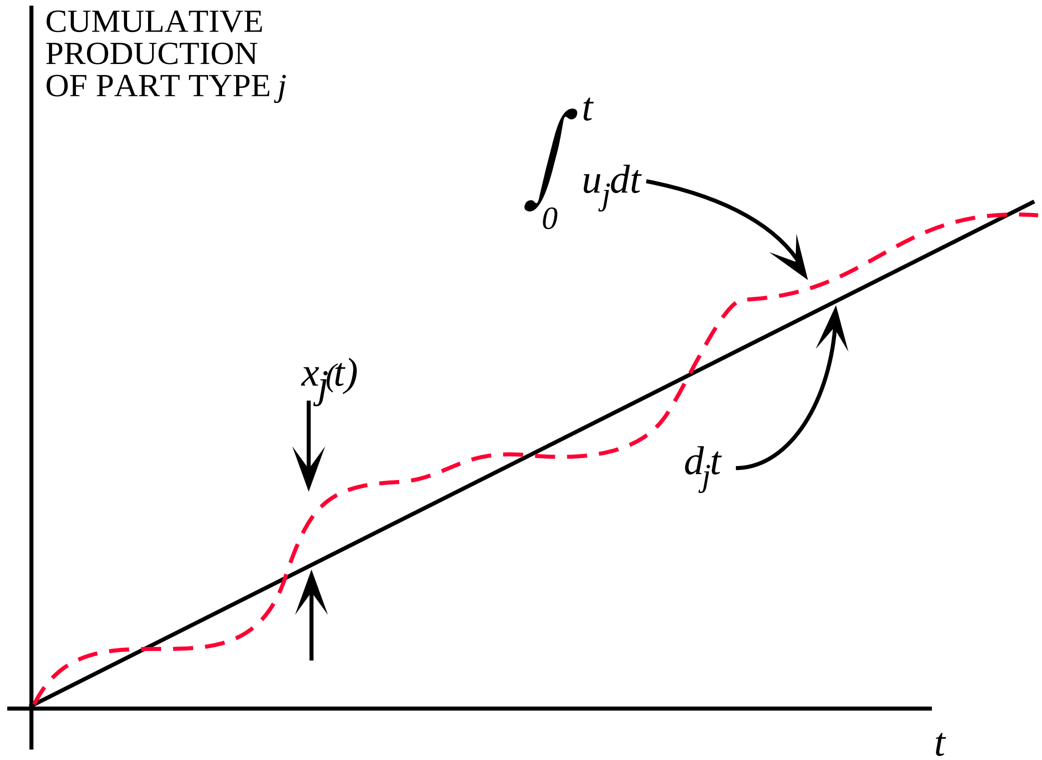
Oldser-Suri, Kimemia-Gershwin formulation

- Single station — no buffers.
- Possibly multiple machines.
- Possibly multiple part types.
- Machine failures and operations are the only important events.
- Operations are much *more frequent* than failures.
- Operations are much *shorter* than failures.
- Changing operations causes no cost or delay.
- The time horizon is very long.
- A long term production rate target is specified, and *is feasible.*
- *essential role of surplus*
- *relationship between surplus and slack*
- *analytical solution for one machine, one part type*

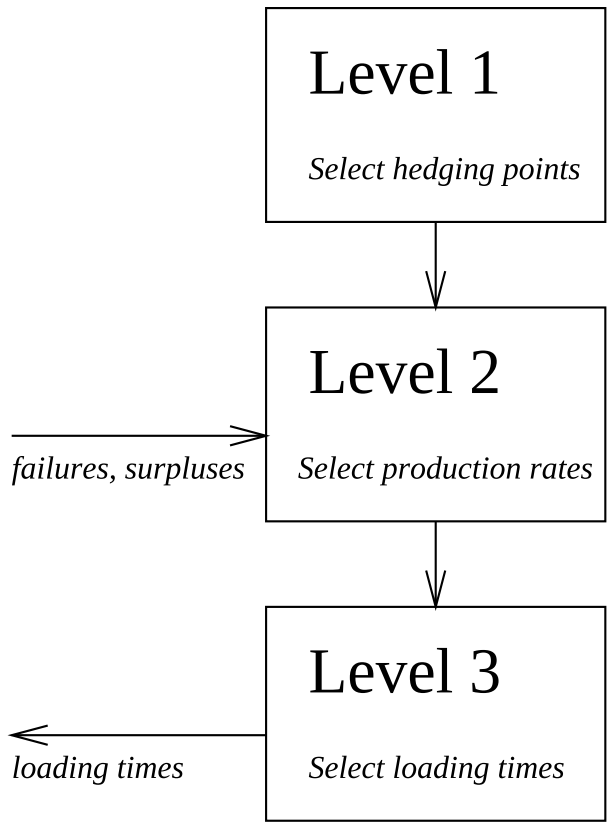
Problem Formulation

- The goal is to meet the long term specified production rate target in a way that keeps inventory and backlog costs small.
- Three-level hierarchy
- Level 1 *determines* Level 2 parameters.
- Level 2 *observes* failures and surpluses, and *determines* short-term production rates.
- Level 3 *determines* loading times.

Cumulative Production and Demand



Three-Level Hierarchy



Hedging Point Problem — variables

- States
  - x = surplus/backlog
  - α = machine state
- Controls
  - u = short-term production rate
- Parameters
  - $\lambda_{\beta\alpha}$ = transition rate matrix; failure and repair rates

    $$\lambda_{\beta\alpha}\delta t = \text{probability of moving from } \alpha \text{ to } \beta \text{ in } (t, t+\delta t)$$
  - d = long-term demand rate target
  - $g()$ cost of surplus and backlog
  - τ_{ij} = operation time of Part Type j at Machine i

Hedging Point Problem — formulation

For large T, find $u(x, \alpha)$ to satisfy

$$\min E \int_0^T g(x(s))ds$$

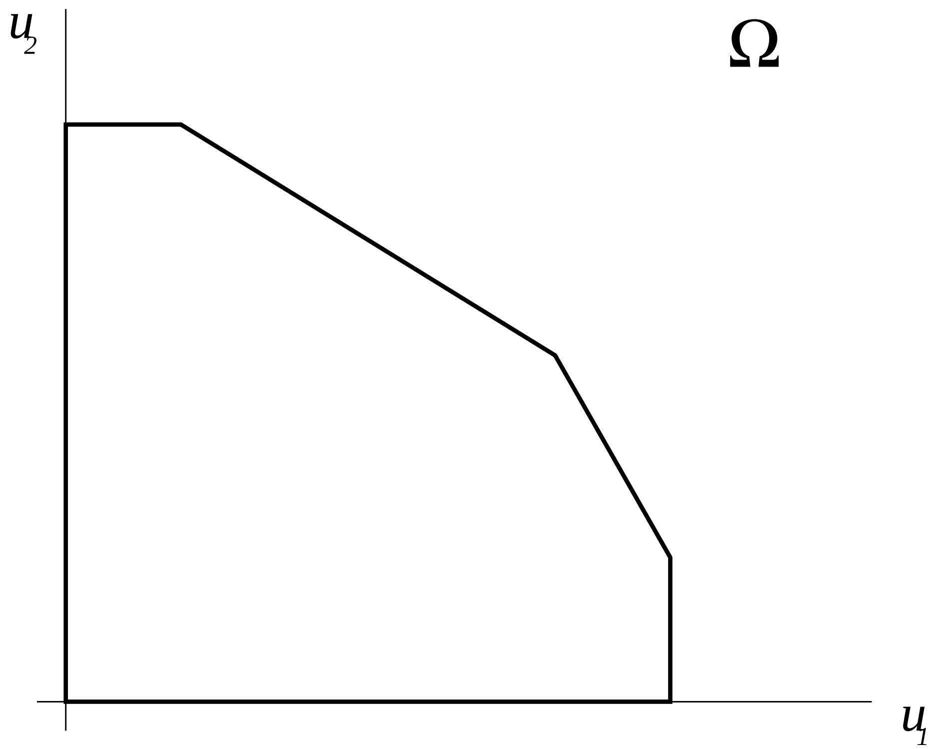
such that

$$\frac{dx}{dt} = u - d$$

Markov dynamics for α

$$u(t) \in \Omega(\alpha(t))$$

Short-Term Capacity Set

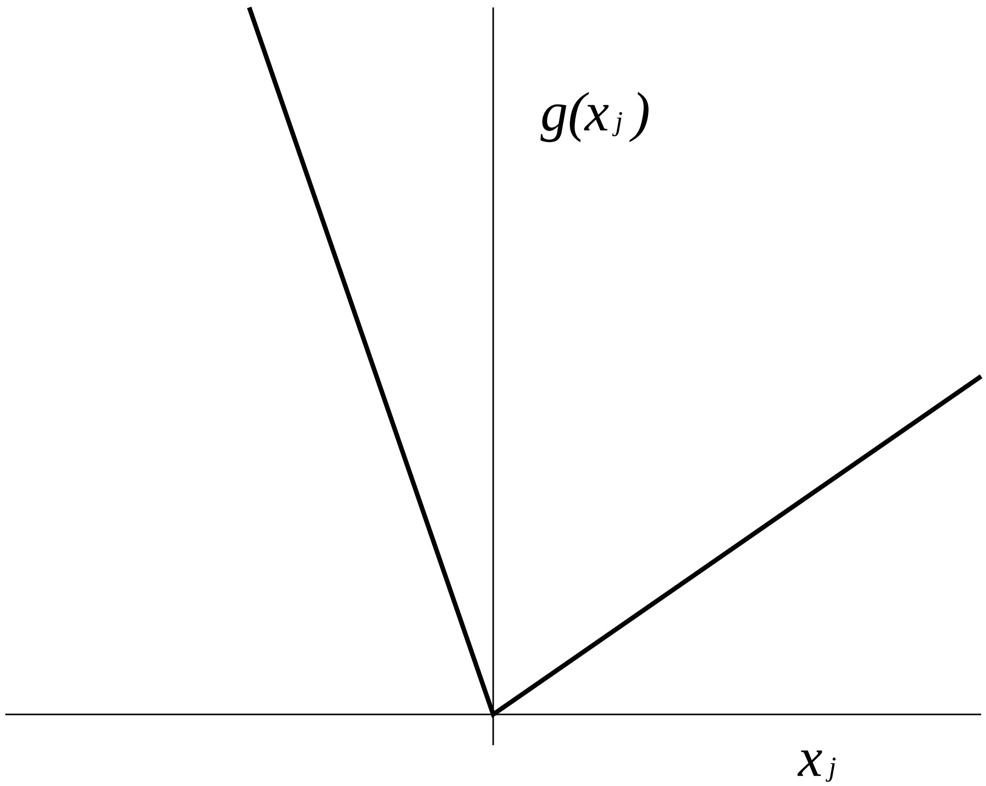


$\Omega(\alpha(t))$ = capacity set:

$$\sum_j \tau_{ij} u_j \leq \alpha_i$$

$$u_j \geq 0$$

Objective Function



$$g(x) = \sum_j g_j(x_j)$$

Hedging Point Problem — solution

Bellman equation:

Let

$$J(x,\alpha,t) = \min E\left\{\int_t^T g(x(s))ds \,\middle|\, x(t)=x, \alpha(t)=\alpha\right\}$$

Then

$$-\frac{\partial J}{\partial t} = \min_{u \in \Omega(\alpha)} \left\{ g(x) + \frac{\partial J}{\partial x}(u-d) + \sum_\beta \lambda_{\beta\alpha} J(x,\beta,t) \right\}$$

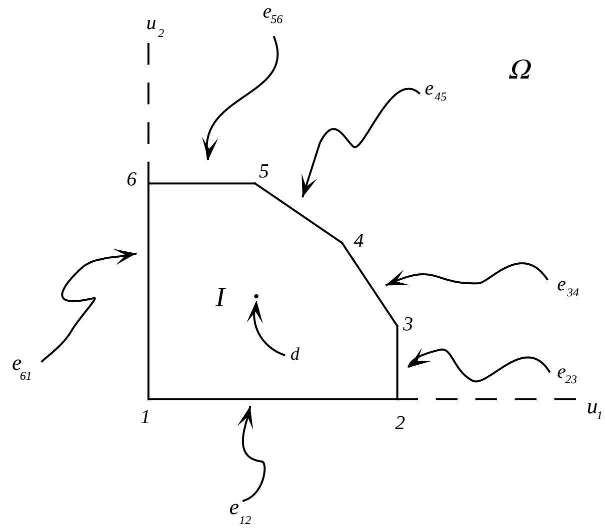
If J were known, u would be determined by the linear program:

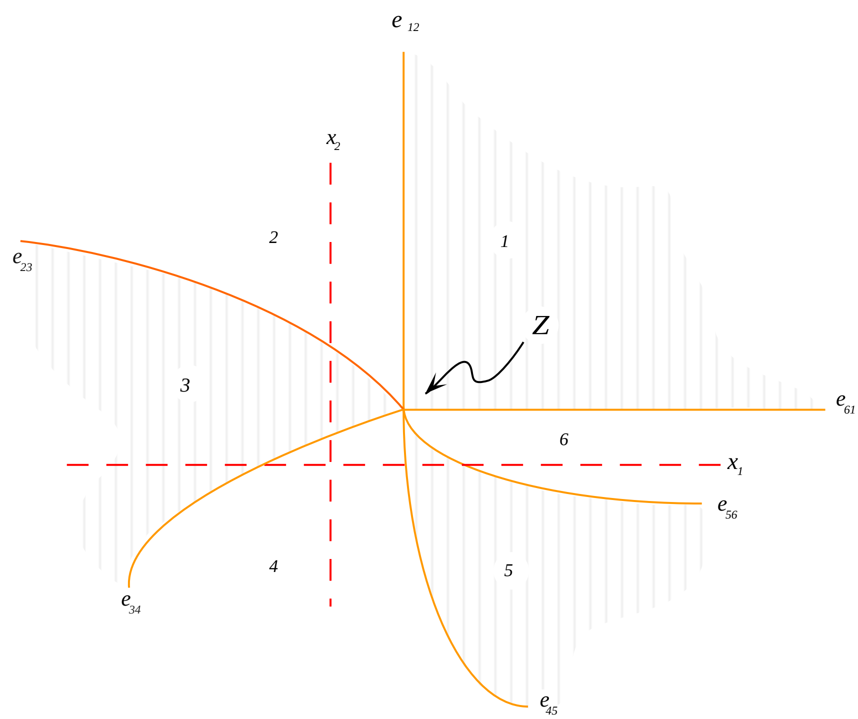
$$\min \frac{\partial J}{\partial x} u$$

subject to

$$u \in \Omega(\alpha)$$

Ω and the Partition of x Space





One-Part-Type, One-Machine Problem

$$g(x) = g_+ x^+ + g_- x^-$$

$$\lambda_{01} = p; \lambda_{11} = -p;$$
$$\lambda_{10} = r; \lambda_{00} = -r.$$

$$\Omega(0) = \{0\},$$
$$\Omega(1) = \{u \mid 0 \leq u \leq \mu\}.$$

where

$\mu = 1/\tau$ is the maximum production rate of the machine.

d is feasible, i.e.,

$$d < \frac{\mu r}{r + p}$$

Hedging Point for One-Part-Type, One-Machine Problem

$$\text{If } g_+ - b(g_+ + g_-) < 0, Z = \frac{\ln\left(Kb(1 + \frac{g_-}{g_+}) > 0\right)}{b}.$$

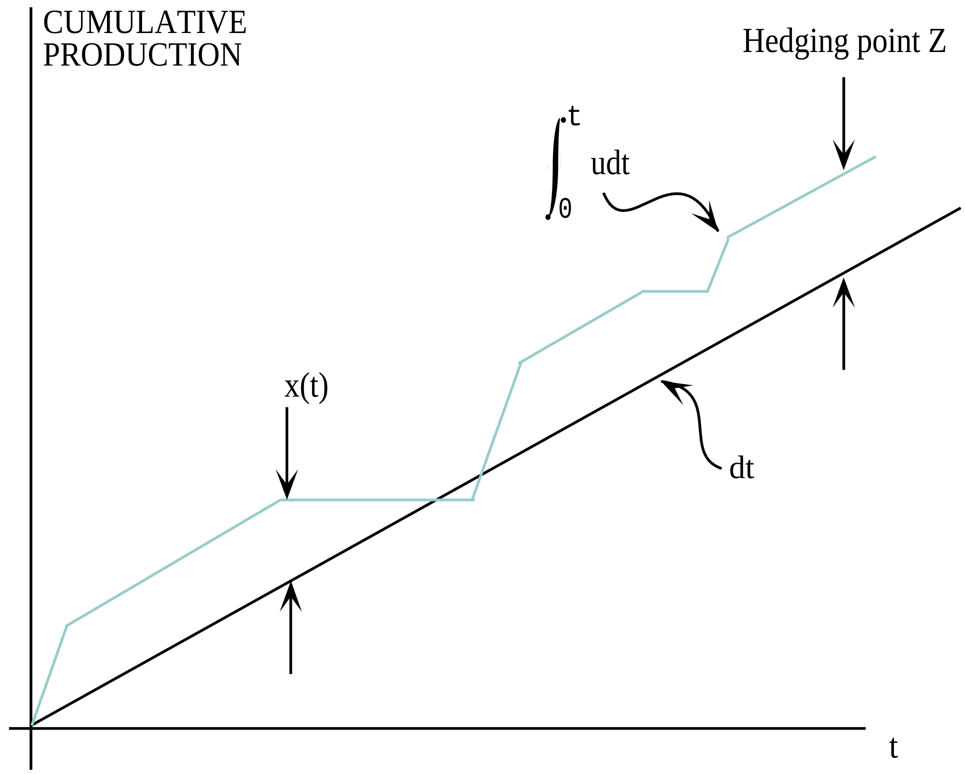
$$\text{If } g_+ - b(g_+ + g_-) \geq 0, Z = 0.$$

where

$$K = \frac{\mu p}{b(r+p)(\mu - d)}$$

$$b = \frac{r}{d} - \frac{p}{\mu - d}$$

Cumulative Production and Demand
Optimal Behavior



Multiple Part Types, Multiple Machines

- **Difficulty:** Bellman equation impossible to solve.
- **Approaches:**
  1. Modify a strategy for a failure-free system.
  2. Approximate the Bellman cost-to-go function with a quadratic:

$$J(x, \alpha, t) \approx J^*(T - t) + \frac{1}{2}(x - Z)^T A(x - Z)$$

Real-Time Controller for First Approach

1. Rank order the products.

2. Produce the most important product, until its surplus reaches its hedging point. The others fall behind.

3. Keep the most important product at its hedging point. Devote all remaining capacity to the *second* most important product, until it reaches its hedging point. The others fall further behind.

4. Keep the two most important products at their hedging points. Devote all remaining capacity to the *third* most important product, until it reaches its hedging point. The others fall still further behind.

5. etc.

6. If there is sufficient capacity, all parts eventually reach their hedging points.

Real-Time Controller for Second Approach

u is determined by the time-varying linear program:

$$\min (x - Z)^T A u$$

subject to

$$\sum_j \tau_{ij} u_j \leq \alpha_j$$

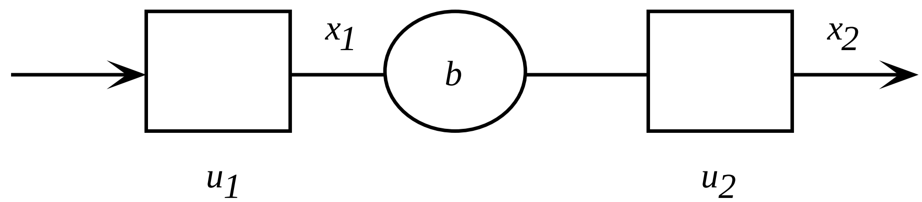
$$u_j \geq 0$$

Special Case: One Machine, Many Part Types

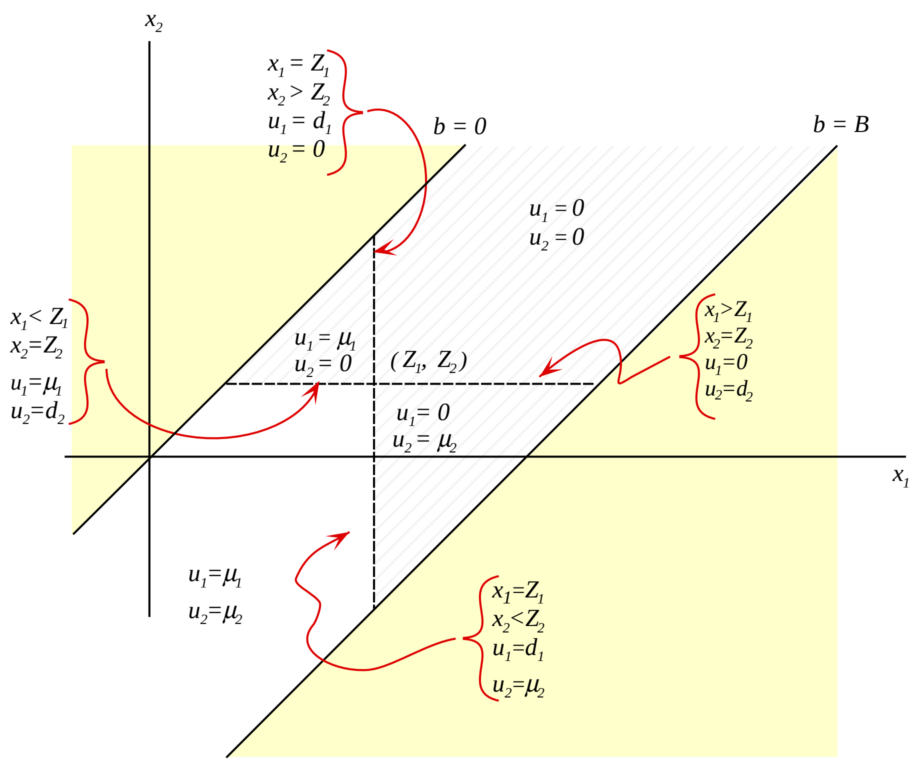
Produce the part that is furthest behind its hedging point.

Van Ryzin-Lou-Gershwin Formulation

- two-station (single-machine per station)



- optimal boundaries determined numerically
- approximate boundaries — *two-boundary policy*

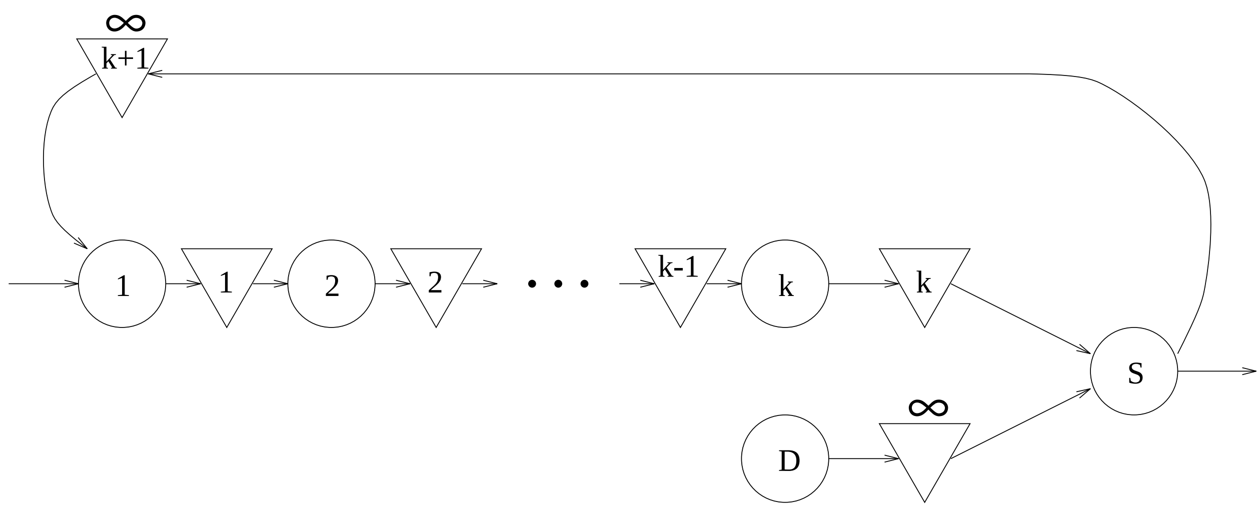


Bai approach

- assumed two-boundary policy for multi-stage system
- simple approximate model to determine optimal buffer sizes and hedging points
- developed for multiple part type system

Networks for Real-time Control

- CONWIP



- two-boundary
- timeliness of information seems to be important issue

-

Motivation for Hierarchy

- *Difficulty* Systems are large and heterogeneous.
- *Goal* Good performance.
- *Constraint* Limited computation.
- *Approach*
  - Decomposition by frequency/duration and location.
  - Develop building blocks – solutions to limited problems.
  - Construct hierarchy from building blocks.

Building Blocks

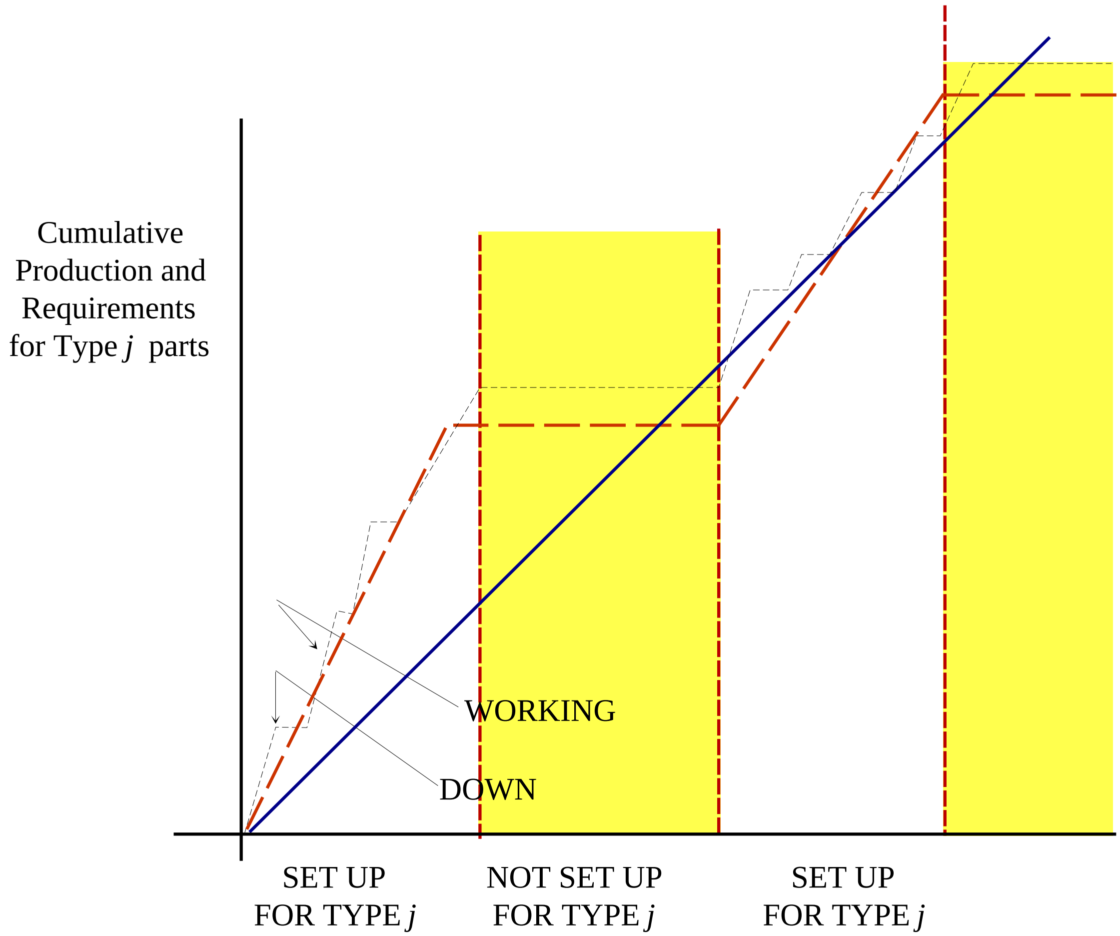
Solve problems with limited frequency range and limited factory floor space.

Input	Relatively long range targets and relatively short range disturbances.
Output	Controllable events and relatively short term targets.
Examples	Hedging point problem/solution.
	Staircase policy.
	Corridor policy.

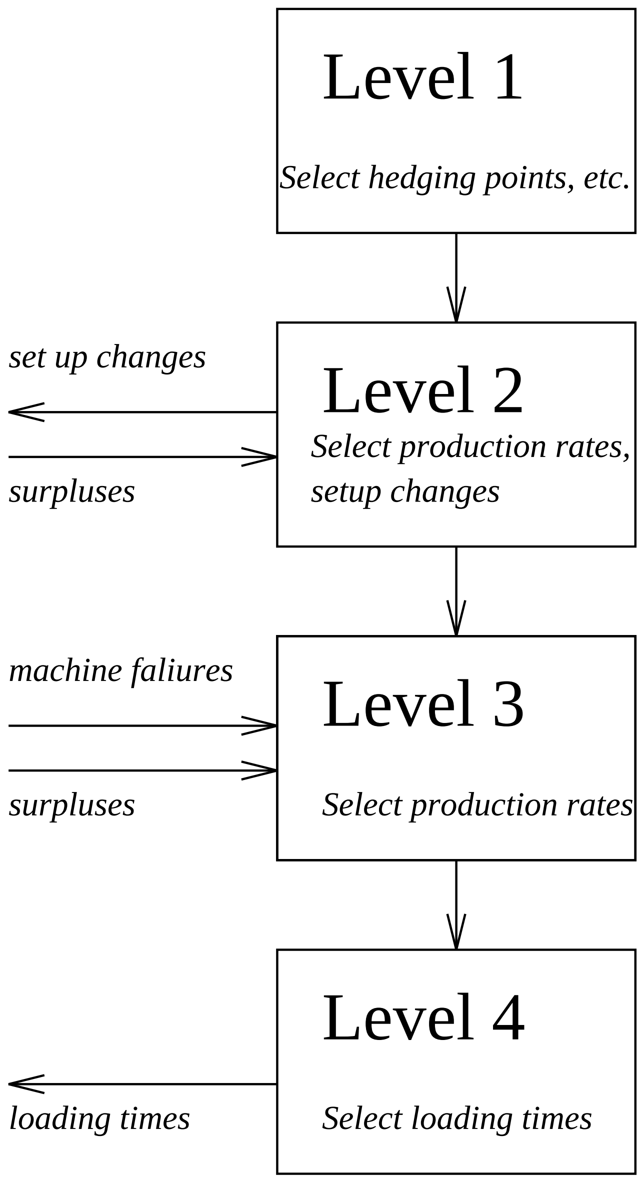
Building Blocks

	Input		Output	
Problem	Continuous	Discrete *(disturbances)*	Continuous	Discrete
Hedging point	Long term production targets	Failures	Short term production targets	—
Hedging point *spatially decomposed*	Long term production targets	Failures, starvations, blockages	Short term production targets	—
Staircase	Long term production targets	—	—	Job release, part loading
Corridor	Long term production targets	—	Short term production targets	Setup changes

Multiple Time Scale Production



Four-Level Hierarchy



Capacity

Capacity is a complex concept because it is

- not a scalar: a *set*;
- not a constant set: a *stochastic set*;
- not a single stochastic set: a *set of sets*, one for each time scale.

Definitions

- A *resource* is any part of the production system that is not consumed or transformed during the production process.
- An *activity* is a pair of events associated with a resource. The first event corresponds to the start of the activity, and the second is the end of the activity. Only one activity can appear at a resource at any time.
- A *disruption* is an undesirable activity.
- Let i be a resource and j an activity. Define $\gamma_{ij}(t)$ to be the *activity state* of Resource i. This is a binary variable which is 1 if Resource i is occupied by Activity j at time t, and 0 otherwise; or

$$\sum_j \gamma_{ij}(t) \leq 1.$$

Production Rate

- Let $N_{ij}(T)$ be the total number of times that Resource i is occupied by Activity j in $(0, T)$.
- Then define the *Activity j frequency* (or *rate*) by

  $$u_{ij} = \frac{1}{T} N_{ij}(T).$$

  (For example, $N(T)$ is *cumulative production* and u is *average production rate.*)
- Let τ_{ij} be the average duration of Activity j at Resource i (e.g., *operation time.*) Then

  $$\tau_{ij} u_{ij} = E\gamma_{ij}.$$

- $E\gamma_{ij}$ is the fraction of time that Machine i is busy doing operations on Part Type j.

Capacity

$$1 \geq E \sum_j \gamma_{ij}(t) = \sum_j \tau_{ij} u_{ij} \text{ for all resources } i.$$

This is the fundamental capacity limitation: no resource can be occupied more than 100% of the time.

Frequency Separation

Assumption

The events and activities can be grouped into sets $\mathcal{L}_1, \mathcal{L}_2, \ldots$ such that for each set $\mathcal{L}_k$, there is a characteristic frequency f_k satisfying

$$0 = f_1 \ll f_2 \ll \ldots \ll f_k \ll f_{k+1} \ll \ldots$$

and

$$j \in \mathcal{L}_k \Rightarrow f_{k-1} \ll u_{ij} \ll f_{k+1}$$

That is, the activities and events in class $\mathcal{L}_k$ have frequencies that are much closer to each other, and to f_k, than to the frequency of any other activity or event.

$k = L(j)$ is the *level* of event $[ij]$.

Example: In one factory, operations are high frequency events, failures are medium frequency events, and setup changes are low frequency events.

Level k Observer

- A *Level k observer or manager* has a precise model only of events that occur with frequencies near f_k.
- The observer has only simplified models of events that occur at frequencies far from f_k.
- **Example:** Low level line managers dispatch repair personnel in reacting to machine failures, and reschedule production on surviving machines.
  - They do not know or care when each operator performs each operation; they only care about hourly or daily quotas.
  - They know that failures and repairs occur with exponential distributions; they know the means of the distributions.
  - They know *nothing* about when the next major setup change will occur except that setup changes are much less frequent than failures.

Level k States

- **Example:** Low level managers know the current repair and setup state of each machine.
- They know the current production rate target of each part type. This target changes as machines go up and down and setup changes occur.
- $\gamma_{ij}^k(t)$ is the *Level k activity state of Resource i*. This is defined, for activities j whose level $L(j)$ is k or higher, as

$$\gamma_{ij}^k(t) = \gamma_{ij}(t) \text{ for } L(j) \leq k.$$

  That is, γ_{ij}^k is the part of γ_{ij} that changes more slowly than f_{k+1}.

Level k Rates

- E_k is the *Level k expectation operator.* It is the conditional expectation, given that all Level m quantities ($\gamma_{ij}^m(t), m \leq k$) remain constant at their values at time t.

- For any random variable z,

$$E_k z(t) = E(z \mid \gamma_{ij}^m = \gamma_{ij}^m(t)$$

$$\text{for all } i, j \text{ such that } L(j) \leq m \leq k).$$

- We define u_{ij}^k, the *Level k rate of Activity j* at Resource i, as

$$u_{ij}^k(t) = \frac{E_k \gamma_{ij}(t)}{\tau_{ij}} \text{ for } L(j) > k.$$

Important Theorem

$$E_{k-1} u_{ij}^{k} = u_{ij}^{k-1} \qquad **$$

This relates rates at different levels of the hierarchy.

Control Problem

- **Problem 1:** Given u_{ij}^{k-1}, find u_{ij}^{k} (for all j, $L(j) > k$) satisfying ** (and other conditions).
- The superior level specifies the goal (u_{ij}^{k-1}) and the lower level must find u_{ij}^{k} to be as close as possible, while satisfying capacity constraints and suffering from high frequency disruptions.

Statistics Problem

- **Problem 2:** Given u_{ij}^k, find u_{ij}^{k-1} (for all j, $L(j) > k$) satisfying ** (and other conditions).
- The lower level specifies the observation (u_{ij}^k) and the higher level must find an average u_{ij}^k.

Research strategy

- Use dynamic programming methods to suggest policy structures.
- Develop decomposition methods to evaluate policies with specified parameters.
- Develop optimization methods as extensions of evaluation methods.

Extensions

- more general networks and policies setups
- quality – yield, quality strategies

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