A Pull Planning Framework

We think in generalities, we live in detail.

—Alfred North Whitehead
Advantages of Pull

Advantages:
- **Observability**: we can see WIP but not capacity.
- **Efficiency**: pull systems require less average WIP to attain same throughput as equivalent push system.
- **Robustness**: pull systems are less sensitive to errors in WIP level than push systems are to errors in release rate.
- **Quality**: pull systems require and promote improved quality.

Magic of Pull: WIP Cap

Hierarchical Pull Planning Framework

Goals:
- To attain the benefits of a pull environment.
- To gain the generality of hierarchical production planning systems.

The Environment:
- CONWIP production lines.
- Daily/Weekly production quota.

The Hierarchy:
- Based on CONWIP for predictability and generality.
- Consistency between levels.
- Accommodate different implementations of modules for different environments.
- Use feedback.

A Dilemma

Question: If pull is so great, why do people still buy ERP systems?

Answer: Manufacturing involves **planning** as well as **execution**.

<table>
<thead>
<tr>
<th>Planning</th>
<th>Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push</td>
<td>good</td>
</tr>
<tr>
<td>Pull</td>
<td>bad</td>
</tr>
</tbody>
</table>

Hierarchical Planning in a Pull System

CONWIP as the Foundation

Pull:
- jobs into the line whenever parts are used.
- jobs with the same routing.
- jobs for different part numbers.

Push:
- jobs between stations on line.
- jobs into buffer storage between lines.

A CONWIP Line:
- represents a level in a bill of material.
- is between stock points.
- maintains a constant amount of work in process.
Benefits of CONWIP

**CONWIP vs. Push:**
- Easier and more robust control.
- Less congestion.
- Greater predictability.

**CONWIP vs. Kanban:**
- Can accommodate a changing product mix.
- Can be used with setups.
- Suitable for short runs of small lots.
- More predictable.

**CONWIP vs. Push:**
- Can accommodate a changing product mix.
- Can be used with setups.
- Suitable for short runs of small lots.
- More predictable.

Conveyor Model of CONWIP

**Predicting Completion Times:**
- Practical production rate: $r_p$ parts per hour
- Minimum practical lead time: $T_p$ hours
- $X_i$ is number of parts in job $i$ on the backlog.

Then the expected completion time of the $n$th job, $c_n$, will be:

$$c_n = \sum_{i=1}^{n} \frac{X_i}{r_p} T_p$$

**Quoting Due Dates:** need to add a “fudge factor” (which should consider cycle time variability) to ensure a reasonable service level.

Forecasting

**Basic Problem:** predict demand for planning purposes.

**Laws of Forecasting:**
1. Forecasts are always wrong!
2. Forecasts always change!
3. The further into the future, the less reliable the forecast will be!

**Forecasting Tools:**
- **Qualitative:**
  - Delphi
  - Analogies
  - Many others
- **Quantitative:**
  - Causal models (e.g., regression models)
  - Time series models

Aggregating Planning by Time Horizon

<table>
<thead>
<tr>
<th>Time Horizon</th>
<th>Length</th>
<th>Representative Decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate-Term (Tactics)</td>
<td>week – year</td>
<td>Work Scheduling, Routing Assignments, Scheduling, Sales Promotion, Inventory Management, Purchasing, Production Planning, Quality Assurance, Health and Safety, Facilities Management, Human Resources</td>
</tr>
</tbody>
</table>

Capacity/Facility Planning

**Basic Problem:** how much and what kind of physical equipment is needed to support production goals?

**Issues:**
- **Basic Capacity Calculations:** stand-alone capacities and congestion effects (e.g., blocking)
- **Capacity Strategy:** lead or follow demand
- **Make-to-Order:** vendor, long-term identity
- **Flexibility:** with regard to product, volume, mix
- **Speed:** scalability, learning curves
Workforce Planning

**Basic Problem:** How much and what kind of labor is needed to support production goals?

**Issues:**
- **Basic Staffing Calculations:** Standard labor hours adjusted for worker availability.
- **Working Environment:** Stability, morale, learning.
- **Flexibility/Agility:** Ability of workforce to support plant’s ability to respond to short and long term shifts.
- **Quality:** Procedures are only as good as the people who carry them out.

Aggregate Planning

**Basic Problem:** Generate a long-term production plan that establishes a rough product mix, anticipates bottlenecks, and is consistent with capacity and workforce plans.

**Issues:**
- **Aggregation:** Product families and time periods must be set appropriately for the environment.
- **Coordination:** AP is the link between the high level functions of forecasting/capacity planning and intermediate level functions of quota setting and scheduling.
- **Anticipating Execution:** AP is virtually always done deterministically, while production is carried out in a stochastic environment.
- **Linear Programming:** A powerful tool well-suited to AP and other optimization problems.

Quota Setting

**Basic Problem:** Set target production quota for pull system

**Benefits:**
- Increased throughput.
- Increased utilization.
- Lower unit labor hour.
- Lower allocation of overhead.

**Costs:**
- More overtime.
- Higher WIP levels.
- More expediting.
- Increased difficulties in quality control.

Planned Catch-Up Times

<table>
<thead>
<tr>
<th>Regular Time</th>
<th>Catch-Up Regular Time</th>
<th>Catch-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>R</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>R+K</td>
<td>2T</td>
</tr>
</tbody>
</table>

Economic Production Quota Notation

- \( p \) = unit profit
- \( C_{ot} \) = fixed overtime cost
- \( Y \) = regular time production (random variable)
- \( \mu \) = mean regular time production \( (E[Y]) \)
- \( \sigma \) = std dev of regular time production \( \sqrt{Var(Y)} \)
- \( M \) = maximum overtime production
- \( Q \) = regular time production quota (decision variable)

Simple “Sell-All-You-Can-Make” Model

**Objective Function:** Average weekly profit

\[
\max_Z = pQ - C_{ot} \Pr[Y \leq Q]
\]

**Reasonability Test:** We want the probability of not being able to catch up on overtime to be small (i.e., \( \alpha \)):

\[
\Pr(Q^* - Y > M) \leq \alpha
\]

If this is not true, another (lost sales) model should be used.
Simple “Sell-All-You-Can-Make” Model (cont.)

Normal Approximation: Express $Q = \mu - k\sigma$, so the objective and reasonability test can be written:

$$\max_{k} Z = p(\mu - k\sigma) - C_{OT} (1 - \Phi(k))$$
$$\Phi(k + M/\sigma) \geq 1 - \alpha$$

Solution: The objective function is maximized by:

$$k^* = \left\lfloor \frac{\ln \left( \frac{C_{OT}}{\frac{\sigma}{\sqrt{2\pi}}} \right)}{\sigma} \right\rfloor$$
$$Q^* = \mu - k^* \sigma$$

Intuition from Model

• Optimal production quota depends on both mean and variance of regular time production ($Q^*$ increases with $\mu$ and decreases with $\sigma$).
• Increasing capacity increases profit, since $\frac{C_{OT}^*}{\sigma^2}$ increases.
• Decreasing variance increases profit, since $\frac{C_{OT}^*}{\sigma^2}$ decreases.
• Model is valid (i.e., has a solution $0 < k^* < \infty$) only if $p < \frac{C_{OT}}{\sqrt{2\pi}\sigma}$

Quota Setting Implementation

• Iteration between quota setting and aggregate planning may be necessary for consistency.
• Motivation (setting the “bar”) vs. Prediction (quoting due dates).
• MPS smoothing – necessary to keep steady quota.
• Gross capacity control through shift addition/deletion, rather than production slow-down.

Other Quota Setting Models (cont.)

Model 4: Backlogging

• Fixed plus variable cost of overtime.
• Dependence between periods requires more sophisticated solution techniques (e.g., dynamic programming).
• Solution consists of $Q^*$, optimal quota, plus $D^*$, an “overtime trigger” such that we use overtime only if the shortage is at least $D^*$.

Other Quota Setting Models

Model 2: Lost Sales

• Run continuously.
• Demand above $Q$ is lost (or vended) at a cost.
• Solution looks like that to the Newsboy problem.

Model 3: Fixed plus Variable Cost of Overtime

• Same as Model 1, except that cost of overtime has a fixed component, $C_{OT}$, and a component proportional to the amount of the shortage.
• Solution looks like that to Model 1 except term under $\sqrt{\cdot}$ is more complex.

Setting WIP Levels

Basic Problem: establish WIP levels (card counts) in pull system.

Issues:

• Mean regular time production increases with WIP level.
• Variance of regular time production also affected by WIP level.
• WIP levels should be set to facilitate desired throughput.
• Adjustment may be necessary as system evolves (feedback).
• Easy method:
  1. Specify feasible cycle time, CT, and identify practical production rate, $r_p$.
  2. Set WIP from $WIP = r_p \times CT$.
Demand Management

Basic Problem: establish an interface between the customer and the plant floor, that supports both competitive customer service and workable production schedules.

Issues:
- Customer Lead Times: shorter is more competitive.
- Customer Service: on-time delivery.
- Batching: grouping like product families can reduce lost capacity due to setups.
- Interface with Scheduling: customer due dates are an enormously important control in the overall scheduling process.

Real-Time Simulation

Basic Problem: anticipate problems in schedule execution and provide vehicle for exploring solutions.

Approaches:
- Deterministic Simulation:
  - Given release schedule and dispatching rules, predict output times.
  - Commercial packages (e.g., FACTOR).
- Conveyor Model:
  - Allow hot jobs to pass in buffers, not in the lines.
  - Use simplified simulation based on conveyor model to predict output times.

Sequencing and Scheduling

Basic Problem: develop a plan to guide the release of work into the system and coordination with needed resources (e.g., machines, staffing, materials).

Methods:
- Sequencing:
  - Gives order of releases but not times.
  - Adequate for simple CONWIP lines where FISFO is maintained.
  - The "CONWIP backlog."
- Scheduling:
  - Gives detailed release times.
  - Attractive where complex routings make simple sequence impractical.
  - MRP-C.

Shop Floor Control

Basic Problem: control flow of work through plant and coordinate with other activities (e.g., quality control, preventive maintenance, etc.)

Issues:
- Customization: SFC is often the most highly customized activity in a plant.
- Information Collection: SFC represents the interface with the actual production processes and is therefore a good place to collect data.
- Simplicity: departures from simple mechanisms must be carefully justified.

Sequencing CONWIP Lines

Objectives:
- Maximize profit.
- No late jobs.
- All firm jobs selected.

Job Sequencing System:
- Sequences bottleneck line.
- Uses Quota to explicitly consider capacity.
- Tries to group like families of jobs to reduce setups.
- Identifies the "offensive" jobs in an infeasible schedule.
- Suggests when more work could start in a lightly loaded schedule.
- Provides sequence for other lines.

Tracking and Feedback

Basic Problems:
- Signal quota shortfall.
- Update capacity data.
- Quote delivery dates.

Functions:
- Statistical Throughput Control:
  - Monitored at critical tools.
  - Like SPC, only measuring throughput.
  - Problems are apparent with time to act.
  - Workers aware of situation.
- Feedback:
  - Collect capacity data.
  - Measure continual improvement.
Conclusions

Pull Environment Provides:
- Less WIP and thereby earlier detection of quality problems.
- Shorter lead times allowing increased customer response and less reliance on forecasts.
- Less buffer stock and therefore less exposure to schedule and engineering changes.

CONWIP Provides: a pull environment that
- Has greater throughput for equivalent WIP than kanban.
- Can accommodate a changing product mix.
- Can be used with setups.
- Is suitable for short runs of small lots.
- Is predictable.

Conclusions (cont.)

Planning Hierarchy Provides:
- Consistent framework for planning.
- Links between levels.
- Feedback.

Forecasting

The future is made of the same stuff as the present.

– Simone Weil

Quantitative Forecasting

Goals:
- Predict future from past
- Smooth out “noise”
- Standardize forecasting procedure

Methodologies:
- Causal Forecasting:
  - regression analysis
  - other approaches
- Time Series Forecasting:
  - moving average
  - exponential smoothing
  - regression analysis
  - seasonal models
  - many others

Time Series Forecasting

Historical Data

Forecast

\[ a(i), i = 1, \ldots \] Time series model

\[ f(t+s), i = 1, 2, \ldots \]
Time Series Approach

Notation:

\( A(i) = \text{observation in period } i, \quad i = 1, \ldots, t \)

\( t = \text{current period} \)

\( f(t + \tau) = \text{forecast for period } t + \tau \)

\( F(t) = \text{smoothed estimate as of period } t \)

\( T(t) = \text{smoothed trend as of period } t \)

Procedure:

1. Select model that computes \( f(t + \tau) \) from \( A(i), \quad i = 1, \ldots, t \)
2. Forecast existing data and evaluate quality of fit by using:

\[
\begin{align*}
\text{MAD} &= \frac{\sum_{t=1}^{n} |f(t) - A(t)|}{n} \\
\text{MSD} &= \frac{\sum_{t=1}^{n} (f(t) - A(t))^2}{n} \\
\text{BIAS} &= \frac{\sum_{t=1}^{n} (f(t) - A(t))}{n}
\end{align*}
\]

3. Stop if fit is acceptable. Otherwise, adjust model constants and go to (2) or reject model and go to (1).

Moving Average

Assumptions:

• No trend
• Equal weight to last \( m \) observations

Model:

\[
F(t) = \sum_{i=1}^{m} \frac{A(i)}{m}
\]

\( f(t + \tau) = F(t), \quad \tau = 1, 2, \ldots \)

Example: Moving Average with \( m = 3 \) and \( m = 5 \).

<table>
<thead>
<tr>
<th>Period (t)</th>
<th>Demand</th>
<th>Forecast (m=3)</th>
<th>Forecast (m=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>11.00</td>
<td>11.33</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>12.33</td>
<td>11.67</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>13.33</td>
<td>12.67</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>15.00</td>
<td>13.67</td>
</tr>
</tbody>
</table>

Note: bigger \( m \) makes forecast more stable, but less responsive.

Exponential Smoothing

Assumptions:

• No trend
• Exponentially declining weight given to past observations

Model:

\[
F(t) = \alpha A(t) + (1 - \alpha) F(t-1)
\]

\( f(t + \tau) = F(t), \quad \tau = 1, 2, \ldots \)
Exponential Smoothing, $\alpha=0.2$

Assumptions:
- Linear trend
- Exponentially declining weights to past observations/trends

Model:
\[
F(t) = \alpha A(t) + (1 - \alpha)[F(t - 1) + T(t - 1)] \\
T(t) = \beta[F(t) - F(t - 1)] + (1 - \beta)T(t - 1) \\
f(t + \tau) = F(t) + \tau T(t)
\]

Note: these calculations are easy, but there is some "art" in choosing $F(0)$ and $T(0)$ to start the time series.

Frank Matejcik  SD School of Mines & Technology

Exponential Smoothing with Trend, $\alpha=0.2$, $\beta=0.5$

Effects of Altering Smoothing Constants

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>MAD</th>
<th>MSD</th>
<th>BIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.77</td>
</tr>
<tr>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.77</td>
</tr>
<tr>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
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<td>0.77</td>
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</table>

Note: these assume we start with trend equal to zero. The table shows the effects of various values of $\alpha$ and $\beta$ on the performance of the Exponential Smoothing with Trend model.
Effects of Altering Smoothing Constants (cont.)

Observations: assuming we start with zero trend
- $\alpha = 0.3, \beta = 0.5$ work well for MAD and MSD
- $\alpha = 0.6, \beta = 0.6$ work better for BIAS
- Our original choice of $\alpha = 0.2, \beta = 0.5$ had MAD = 3.73, MSD = 22.32, BIAS = -2.02, which is pretty good, although $\alpha = 0.3, \beta = 0.5$, with MAD = 3.65, MSD=21.78, BIAS = -1.32 is better.

Winters Method Example

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Our original choice of $\alpha = 0.5, \beta = 0.3$ had MAD, MSD, BIAS of 3.65, 21.78, -2.02. The trend: $T(t) = 0.5 + 0.3(t-1)$, with MAD = 3.62, MSD = 22.32, BIAS = -1.32 is better.
Shop Floor Control

Even a journey of one thousand li begins with a single step.

– Lao Tze

It is a melancholy thing to see how zeal for a good thing abates when the novelty is over, and when there is no pecuniary reward attending the service.

– Earl of Egmont

What is Shop Floor Control?

Definition: Shop Floor Control (SFC) is the process by which decisions directly affecting the flow of material through the factory are made.

Functions:

- WIP Tracking
- Throughput Tracking
- Status Monitoring
- Work Forecasting
- Capacity Feedback
- Quality Control
- Material Flow Control
- Feedback
- Work Forecasting
- Quality Control
- Material Flow Control

Planning for SFC

Gross Capacity Control: Match line to demand via:
- Varying staffing (no. shifts or no. workers/shift)
- Varying length of work week (or work day)
- Using outside vendors to segment capacity

Bottleneck Planning:
- Bottlenecks can be designed
- Cost of capacity is key
- Stable bottlenecks are easier to manage

Span of Control:
- Physically or logically decompose system
- Span of labor management (10 subordinates)
- Span of process management (related technology?)

Basic CONWIP

Rationale:
- Simple starting point
- Can be effective

Requirements:
- Constant routings
- Similar processing times (stable bottleneck)
- No significant setups
- No assemblies

Design Issues:
- Work backlog – how to maintain and display
- Line discipline – FIFO, limited passing
- Card counts – WIP = CT \times r, initially, then conservative adjustments
- Card deficits – violate WIP-cap in special circumstances
- Work ahead – how far ahead relative to due date?

CONWIP Line Using Cards

Card Deficits

Jobs without Cards

Jobs with Cards

Bottleneck Process

Failed Machine
Tandem CONWIP Lines

Links to Kanban: when “loops” become single process centers

Bottleneck Treatment:
- Nonbottleneck loops coupled to buffer inventories (cards are released on departure from buffer)
- Bottleneck loops uncoupled from buffer inventories (cards are released on entry into buffer)

Shared Resources:
- Sequencing policy is needed
- Upstream buffer facilitates sequencing (and batching if necessary)

Tandem CONWIP Loops

Basic CONWIP

Multi-Loop CONWIP

Kanban

Workstation Buffer Card Flow

Coupled and Uncoupled CONWIP Loops

Bottleneck

CONWIP Loop Buffer Job

CONWIP Card Material Flow Card Flow

Splitting Loops at Shared Resource

Routing A

Routing B

CONWIP Loop

Buffer

Material Flow Card Flow

Modifications of Basic CONWIP

Multiple Product Families:
- Capacity-adjusted WIP
- CONWIP Controller

Assembly Systems:
- CONWIP achieves synchronization naturally (unless passing is allowed)
- WIP levels must be sensitive to “length” of fabrication lines

CONWIP Controller

Work Backlog

Indicator Lights

Workstations

LAN
**CONWIP Assembly**

Processing Times for Line A

Processing Times for Line B

Buffer \[\rightarrow\] Card Flow \[\rightarrow\] Material Flow

**Pull From the Bottleneck**

**Problems with CONWIP/Kanban:**
- Bottleneck starvation due to downstream failures
- Premature releases due to CONWIP requirements

**PFB Remedies:**
- PFB ignores WIP downstream of bottleneck
- PFB launches orders when bottleneck can accommodate them

**PFB Problem:**
- Floating bottlenecks

**Kanban**

**Advantages:**
- Improved communication
- Control of shared resources

**Disadvantages:**
- Complexity – setting WIP levels
- Tighter pacing – pressure on workers, less opportunity for work ahead
- Part-specific cards – can’t accommodate many active part numbers
- Inflexible to product mix changes
- Handles small, infrequent orders poorly

**Simple Pull From the Bottleneck**

**Routings in a Jobshop**

**Kanban with Work Backlog**

**Material Flow** \[\rightarrow\] **Card Flow**

**Kanban with Work Backlog**

**Material Flow** \[\rightarrow\] **Card Flow**

**Routings in a Jobshop**

**ASSEMBLY**

**BOTTLENECK**

**Backlog**

1 2 3 4
Implementing PFB

Notation:
- \( b_i \): The time required on the bottleneck by job \( i \) on the backlog.
- \( t_i \): The average time after release required for job \( i \) to reach the bottleneck.
- \( L \): The specified time for jobs to wait in the buffer in front of the bottleneck.

Work at Bottleneck: total hours of work ahead of job \( j \) is \( \sum b_i \).

Job Release Mechanism: Release job \( j \) whenever \( \sum b_i \leq t_j + L \).

Enhancement: establish due date window, before which jobs are not released.

STC Mechanics

Assumption: \( N_t \) is normally distributed with mean \( \mu R \) and variance \( \sigma^2 R \).

Implications:
- \( N_t \) is normally distributed with mean \( \mu R \) and variance \( \sigma^2 R \).
- If \( N_t = n_t \) where \( n_t \leq Q_t \), we will miss quota only if \( N_t > Q_t - n_t \).

Formula: The probability of missing quota by time \( R \) given an overage of \( x \) is

\[
P(N_t > Q_t - x/R) = \Phi(z_R) - \Phi\left(\frac{Q_t - x}{\sigma^2 R / R^2}\right)
\]

STC Charts

Motivation: information “at a glance”

Computations: Pre-compute the overage levels that cause the probability of missing quota to be a specified level \( \alpha \):

\[
\Phi\left(\frac{Q_t - \mu R - x}{\sigma^2 R / R^2}\right) = \alpha
\]

which yields

\[
z = \frac{(Q_t - \mu R - x)}{\sigma^2 R / R^2} = \sqrt{\frac{R}{\sigma^2}} z
\]

where \( z \) is chosen such that \( \Phi(z) = \alpha \).

STC Notation

- \( R \): length of regular time
- \( \mu \): mean production during regular time
- \( \sigma \): standard deviation of regular time production
- \( Q \): production quota
- \( N_t \): production in \([0,t]\)
- \( Y_t \): time to make quota in \( n^* \) regular time period
- \( \mu_q \): mean time to make quota, \( E[Y_t] \)
- \( \sigma_q \): std dev of time to make quota, \( \sqrt{\text{Var}(Y_t)} \)

Note: we might have these instead of \( \mu \) and \( \sigma \) if we stop when quota is made.
Long-Range Tracking

Statistics of Interest:
- \( \mu \): mean production during regular time
- \( \sigma^2 \): variance of regular time production

Observable Statistics: if we stop when quota is achieved, then instead of \( \mu \) and \( \sigma \) we observe
- \( \bar{\mu}_S \): mean time to make quota
- \( \sigma^2_S \): variance of time to make quota

Conversion Formulas: If we have \( \bar{\mu}_S \) and \( \sigma^2_S \), then we can smooth these (as shown later) and then convert to \( \mu \) and \( \sigma \) by using
\[
\mu = \frac{RQ}{\bar{\mu}_S}, \quad \sigma^2 = \frac{\sigma^2_S RQ^2}{\bar{\mu}_S^2}
\]

Smoothing Capacity Parameters

Mean Production:
\[
\hat{\mu}(n) = a\hat{\mu}_{n-1} + (1-a)(\hat{\mu}(n-1) + \hat{T}_{n-1})
\]
\[
\hat{T}(n) = \beta(\hat{\mu}(n) - \hat{\mu}(n-1)) + (1-\beta)\hat{T}(n-1)
\]
- where \( a \) and \( \beta \) are smoothing constants.

Production Variance:
\[
\hat{\sigma}^2(n) = \gamma(\hat{\sigma}^2_{n-1} + (1-\gamma)\hat{\sigma}^2(n-1))
\]
- where \( \gamma \) is a smoothing constant.
Shop Floor Control Takeaways

General:
- SFC is more than material flow control (WIP tracking, QC, status monitoring, …)
- Good SFC requires planning (workforce policies, bottlenecks, management, …)

CONWIP:
- Simple starting point
- Reduces variability due to WIP fluctuations
- Many modifications possible (kanban, pull-from-bottleneck)

Shop Floor Control Takeaways (cont.)

Statistical Throughput Control (STC):
- Tool for OT planning/prediction
- Intuitive graphical display

Long Range Tracking:
- Feedback for other planning/control modules
- Exponential smoothing approach