In Search of the Production Steady State: Mission Impossible?

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Presenter Overview

- Technomics Detroit Office Manager (2018-Present)
- Booz Allen Hamilton – Troy, MI Office Cost Team Lead (2015-2018)
- General Dynamics Land Systems (GDLS) Anniston, AL – Sr. Industrial Engineer and Production Team Lead (2007-2009)
- GDLS HQs, Sterling Heights, MI – Sr. Industrial Engineer (2002-2007)
- DAWIA Level III Certified in Contracting
- DAWIA Level I Certified in Program Management
- CCEA Certified (March 2016)
- Vice President – ICEAA Detroit Chapter
- PMP Certified (March 2020)
- BS and MS degrees in Industrial Engineering from Purdue University

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Program Manager & Technomics Detroit Office Lead

Overview

- Learning Curve Theory Recap
- Individual vs Organizational Learning
- Why Should we Care About the Production Steady State?
- Defining the Steady State
- Example
- Beware of False Alarms
- Potential Remedies
- Conclusions and Recommendations
- Q&A
Learning Curve Theory Recap

- General definition of learning curve theory:
  “A measure of progress or improvement observed in a constant system as the number of repetitions to complete a task or units produced increase over time”

- In production environments, we look at rate of reduction with regards to resources required (e.g. labor hours) over a period of time for the production of multiple units with the key variables remaining the same:
  - Production rate or throughput
  - The employees performing the work
  - The facility, tools and equipment used
  - The scope of the work being performed (including the materials and sub-assemblies used)
  - Quality requirements
  - Safety Requirements
  - Labor Laws

Crawford (Unit Curve)
- \[ Y = aX^b \]
  - \( Y \) = Cost of the \( X \)th unit
  - \( a \) = Theoretical cost (T1) of the first unit in the production run
  - \( X \) = Sequential unit number of unit being calculated
  - \( b \) = \( \log_2(\text{LCS}) \), a constant reflecting the rate of cost decrease from unit to unit
  - LCS = Learning Curve Slope (aka – The rate of learning)

Wright (Cum Avg Curve)
- \[ Y = \text{Cumulative average cost of } X \text{ units} \]
  - \( Y \) = Cumulative average cost of \( X \) units
  - \( a \) = Theoretical cost (T1) of the first unit in the production run
  - \( X \) = Sequential unit number of unit being calculated
  - \( b \) = \( \log_2(\text{LCS}) \), a constant reflecting the rate of cost decrease from unit to unit
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Individual vs Organizational Learning

**Individual Learning**

“Improvement demonstrated by an individual worker or entire workforce while utilizing a constant product design and constant tools and equipment”

- Example - Production environment for new program
  - Brand new staff all start on day 1
  - Flexible Schedule
  - Tooling/Fixtures/Scope Static

**Organizational Learning**

“Changing product design, changing tools and equipment, and changing work methods”

- Example - Production environment for new program
  - Staff ramps up according to schedule
  - Variable production rate
  - Updated tooling/fixtures
  - ECPs

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Why Should We Care About the Steady State? – Part I

- Avoid underestimating direct labor hours:

```
<table>
<thead>
<tr>
<th>Steady State Starting Unit</th>
<th>1,000</th>
<th>750</th>
<th>500</th>
<th>250</th>
<th>100</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Hours Required</td>
<td>257,918</td>
<td>259,754</td>
<td>267,905</td>
<td>294,340</td>
<td>349,466</td>
<td>405,155</td>
</tr>
<tr>
<td>Difference in Hours Required</td>
<td>N/A</td>
<td>1,836</td>
<td>9,987</td>
<td>36,422</td>
<td>91,548</td>
<td>147,237</td>
</tr>
<tr>
<td>% Increase in Hours</td>
<td>N/A</td>
<td>0.7%</td>
<td>3.9%</td>
<td>14.1%</td>
<td>35.5%</td>
<td>57.1%</td>
</tr>
</tbody>
</table>
```
Why Should We Care About the Steady State? – Part II

- Identifying the steady state requirements provides a static point of reference for making critical decisions about how an environment could and should operate.
- Key variables and studies that are informed by steady state conditions:
  - Staffing Plan
  - Line Balancing/Bottleneck Analysis
  - Throughput Analysis
  - Commonality Across End Items
  - Cycle Times
  - Efficiency Limits
  - Discrete Event Simulation
  - Facility Layout and Design
  - Business Case & Cost Benefit Analyses
Steady State Defined

- In **continuous time**, this means that for those properties $p$ of the system, the partial derivative with respect to time ($t$) is zero and remains so:
  \[
  \frac{\delta p}{\delta t} = 0,
  \]
  for all present and future $t$

- In **discrete time**, it means that the first difference of each property is zero and remains so:
  \[
  p_t - p_{t-1} = 0,
  \]
  for all present and future $t
Production Steady State Defined

Textbook Definition

“For a system to be in steady state, the parameters of the system must never change and the system must have been operating long enough that the initial conditions no longer matter”

- Highly unlikely to ever see this in DoD weapon system production environments (Low to mid production rates)
  - Facility/Equipment/Tooling Issues
  - Staffing Irregularities (sick, vacation, etc.)
  - Supplier Quality Defects

Proposed DoD Production Systems Definition

“In weapon system production environments, the steady state commences at unit n when the probability of unit n+1’s hours being higher than those required for n are equal to the probability unit n+1’s hours being lower than those required for n”

- \( p_{n+1, h} = p_{n+1, l} = 0.5 \), where:
  - \( p_{n+1, h} \) = Probability of Unit n+1 requiring the same amount or more direct labor hours than unit n
  - \( p_{n+1, l} \) = Probability of Unit n+1 requiring same amount or less direct labor hours than unit n

Production Steady State Identification

- Based on our definition, what we are looking for is when our system becomes a **stationary process**
- A stationary process consists of time-series data that does not have any upward or downward trend or seasonal effects, if applicable
- Propose a three-step approach to identifying when and if a system is stationary
  - Visual analysis (e.g. plots)
  - Binning the data and analyzing if system metrics (e.g. mean and variance) stay relatively constant
  - Statistical Testing
    - Dickey-Fuller
    - Kwiatkowski-Phillips-Schmidt-Shin (KPSS)
Example - Identifying the Steady State

- System Overview
  - Plot of data for a commercial wheeled vehicle system with a BWS of 330.0 hours/unit
  - Interested in using this system to predict labor requirements for a new, comparable DoD system
Example - Identifying the Steady State

Step 1: Plot the Data

- Conclusions: Data appears to be broken into three distinct sections
  - Section 1: Individual Learning
  - Section 2: Steady State, but with ongoing variability
  - Section 3: After a sharp spike, a second steady state, but with a lower HPU
Example - Identifying the Steady State

Step 1a: Plot the Data

- Conclusion 1: Steady state appears to occur between units 201 and 538
- Conclusion 2: Variability is clearly present in data set, but it does seem evenly distributed above and below the mean without any obvious trends
Example - Identifying the Steady State

Step 2: Bin the Data

- Conclusion 1: Binning the data into 10 (almost) equally sized groups reveals limited variance in the mean across bins.
- Conclusion 2: There appears to still be a noticeable amount of variability between the measured variance for the bins.

![Graph showing binning of data and variability](image)

- **Mean** = 364.16

<table>
<thead>
<tr>
<th>Bin 1</th>
<th>Bin 2</th>
<th>Bin 3</th>
<th>Bin 4</th>
<th>Bin 5</th>
<th>Bin 6</th>
<th>Bin 7</th>
<th>Bin 8</th>
<th>Bin 9</th>
<th>Bin 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qty</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Mean</td>
<td>367.02</td>
<td>364.50</td>
<td>361.69</td>
<td>363.42</td>
<td>368.00</td>
<td>365.32</td>
<td>363.43</td>
<td>363.10</td>
<td>361.69</td>
</tr>
<tr>
<td>Variance</td>
<td>187.22</td>
<td>182.90</td>
<td>211.49</td>
<td>228.38</td>
<td>203.02</td>
<td>258.02</td>
<td>197.80</td>
<td>252.73</td>
<td>212.64</td>
</tr>
</tbody>
</table>
Step 3: Statistical Testing

- Test for Stationarity using Dickey-Fuller Test
  - The Dickey-Fuller test considers a stochastic process \((y_n)\): \(y_n = \phi y_{n-1} + \varepsilon_n\), where \(\phi \leq 1\) and \(\varepsilon_n\) is white noise. If \(\phi = 1\), a unit root exists and the system is not stationary. If \(\phi < 1\), the process is stationary.

- When considering the differences for consecutive values of \(y_n\) we can define \(\Delta y_n = y_n - y_{n-1}\) and \(\beta = \phi - 1\). What we get is a linear regression equation: \(\Delta y_n = \beta y_{n-1} + \varepsilon_n\), where \(\beta \leq 0\)

- Linear regression can be used for a one tailed test as \(\beta\) cannot be positive, however, we can’t use the usual t test

- The coefficient follows a tau distribution. Testing tau statistic \(\tau\) (which is equivalent to the usual t statistic) is less than \(\tau_{crit}\) based on a table of critical tau statistics values shown in the Dickey-Fuller Table

- Null Hypothesis \((H_0)\): If accepted, it suggests the time series has a unit root and is non-stationary. It has some time dependent structure

- Alternative Hypothesis \((H_1)\): The null hypothesis is rejected; it suggests the time series does not have a unit root and is stationary

Example - Identifying the Steady State

Example - Identifying the Steady State

Step 3: Statistical Testing

\[ \Delta y = y_n - y_{n-1} \]

Perform Regression Analysis

<table>
<thead>
<tr>
<th>Unit #</th>
<th>HPU</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>369.6</td>
<td>N/A</td>
</tr>
<tr>
<td>202</td>
<td>368.3</td>
<td>-1.28</td>
</tr>
<tr>
<td>203</td>
<td>379.6</td>
<td>11.31</td>
</tr>
<tr>
<td>204</td>
<td>341.9</td>
<td>-37.68</td>
</tr>
<tr>
<td>205</td>
<td>348.2</td>
<td>6.30</td>
</tr>
<tr>
<td>206</td>
<td>353.3</td>
<td>5.03</td>
</tr>
<tr>
<td>207</td>
<td>372.1</td>
<td>18.87</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>537</td>
<td>354.8</td>
<td>-5.02</td>
</tr>
<tr>
<td>538</td>
<td>371.9</td>
<td>17.06</td>
</tr>
</tbody>
</table>

Conclusion

- Reject \( H_0 \) with a high degree of confidence. However, we should explore what is causing the variance within the data.

Compare \( t \) statistic w/ Critical Values
Completing the Estimate

Estimating Hours for New DoD System

- Brand new staff
- 1,000 units, BWS = 258.75 hours per unit
- Delivery schedule/rate is comparable to commercial line

\[
y = 1249.6x^{-0.234} \\
R^2 = 0.9725
\]

\[
LCS = 2^{-0.234} = 85.0\%
\]

Steady State Efficiency = BWS/HPU_{SS}

\[
= 330.0/364.16 = 90.6\%
\]

Completing the Estimate

Estimating Hours for New DoD System

- Brand new staff
- 1,000 units, BWS = 258.75 hours per unit
- Delivery schedule/rate is comparable to commercial line

\[ Y = 990.3 \times X^{-0.234} \]
For Units 1-200

Since \( 285.6 = T_1 \times 201^{-0.234} \),
\[ T_1 = 990.3 \]

\[ \text{HPU}_{SS} = \frac{\text{BWS}}{\text{Efficiency}} = \frac{258.75}{0.906} = 285.6 \text{ Hours per Unit} \]
For Units 201-1000

Beware of False Alarms

- On occasion, production data can mislead us.
- It is not uncommon to have Organizational Learning counteract the Individual Learning still occurring.
- The fourth, and most important step, in verifying a steady state is to investigate the system.
Potential Remedies

- ALWAYS start with a visual display of the data
- Analyze the curve in multiple sections if deviations or trends are obvious
- Communicate with SMEs
  - Human Resources: Attrition statistics or bumping due to down-sizing
  - Industrial Engineering/Production Management: Production rate data, including staffing levels and efficiency reports relative to the BWS at particular times
  - Manufacturing Engineering: New technology and modifications to scope
  - Program Management: Business base changes
- DO NOT attempt to predict Organizational Learning
Conclusions and Recommendations

- Identifying when a system enters into steady state can have a significant impact on how we estimate requirements for future items.

- Utilizing a three-step process can help us determine whether or not a system or process has become stationary:
  - Plot the data
  - Bin the data
  - Statistical Testing

- It is important that we identify where Organizational Learning has occurred in past systems.

- The fourth step, communication with SMEs, will help us determine whether we should trust the data and our analysis or if we are being misled.

- It is even more important that we try not to predict when Organizational Learning will occur in the future.