Technomics
Better Decisions Faster

In Search of the Production Steady State: Mission Impossible?

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Presenter Overview

Pat McCarthy
Program Manager & Technomics Detroit Office Lead

- Technomics Detroit Office Manager (2018-Present)
- Booz Allen Hamilton – Troy, MI Office Cost Team Lead (2015-2018)
- Army Contracting Command (ACC) Warren, MI – Industrial Price/Cost Analyst and Team Lead (2009-2015)
- 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

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 = **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 = log2(LCS), a constant reflecting the rate of cost decrease from unit to unit
- LCS = Learning Curve Slope (aka – The rate of learning)

$$Y = aX^b$$

Wright (Cum Avg Curve)

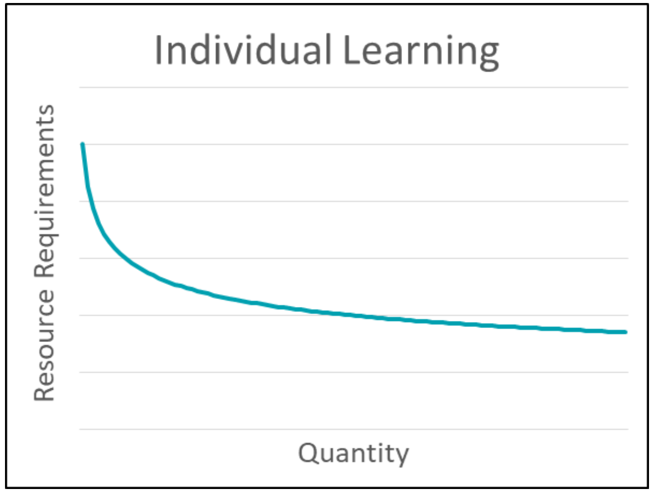
- Y = **Cumulative average cost of X units**
- a = Theoretical cost (T1) of the first unit in the production run
- X = Sequential unit number of unit being calculated
- b = log2(LCS), a constant reflecting the rate of cost decrease from unit to unit
- LCS = Learning Curve Slope (aka – The rate of learning)

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*"[1]

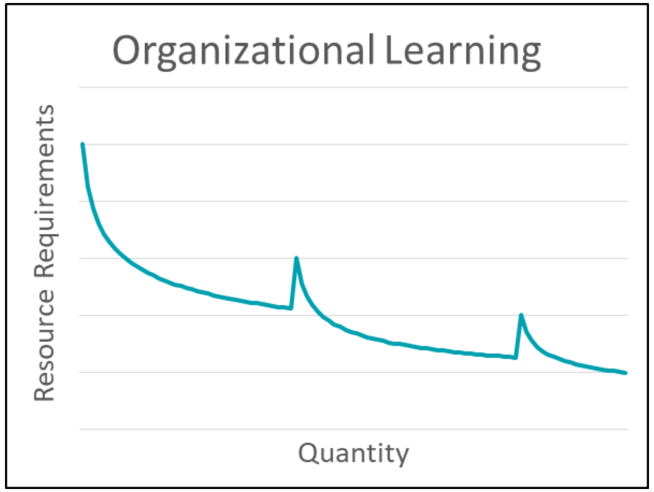
- Example - Production environment for new program
  - Brand new staff all start on day 1
  - Flexible Schedule
  - Tooling/Fixtures/Scope Static



Organizational Learning

"*Changing product design, changing tools and equipment, and changing work methods*"[1]

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



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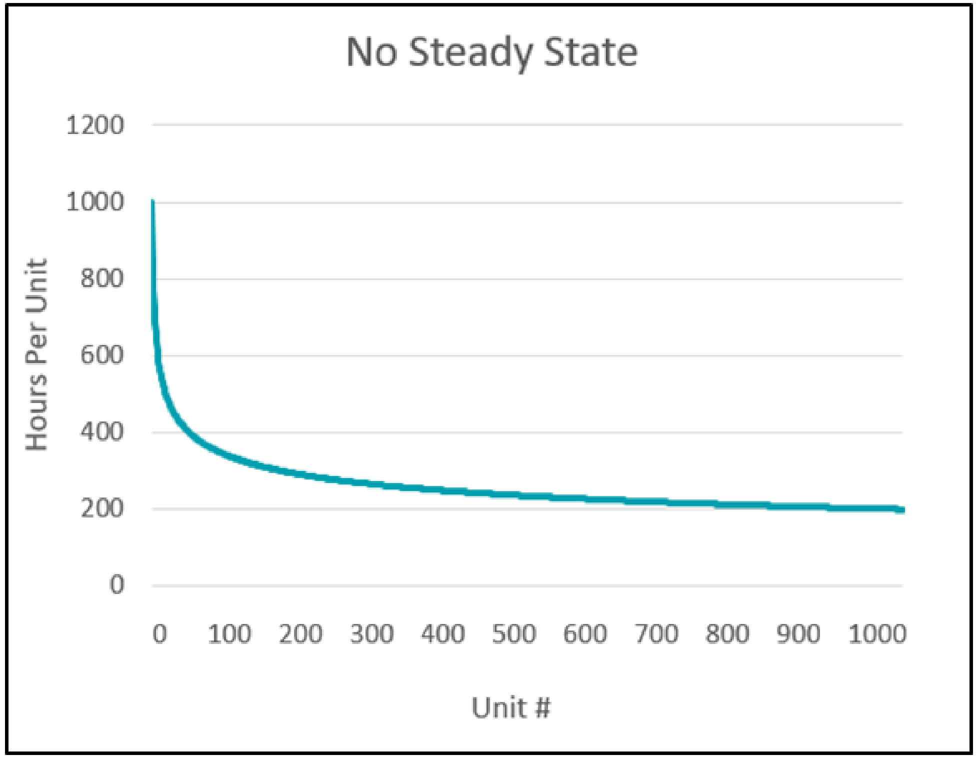
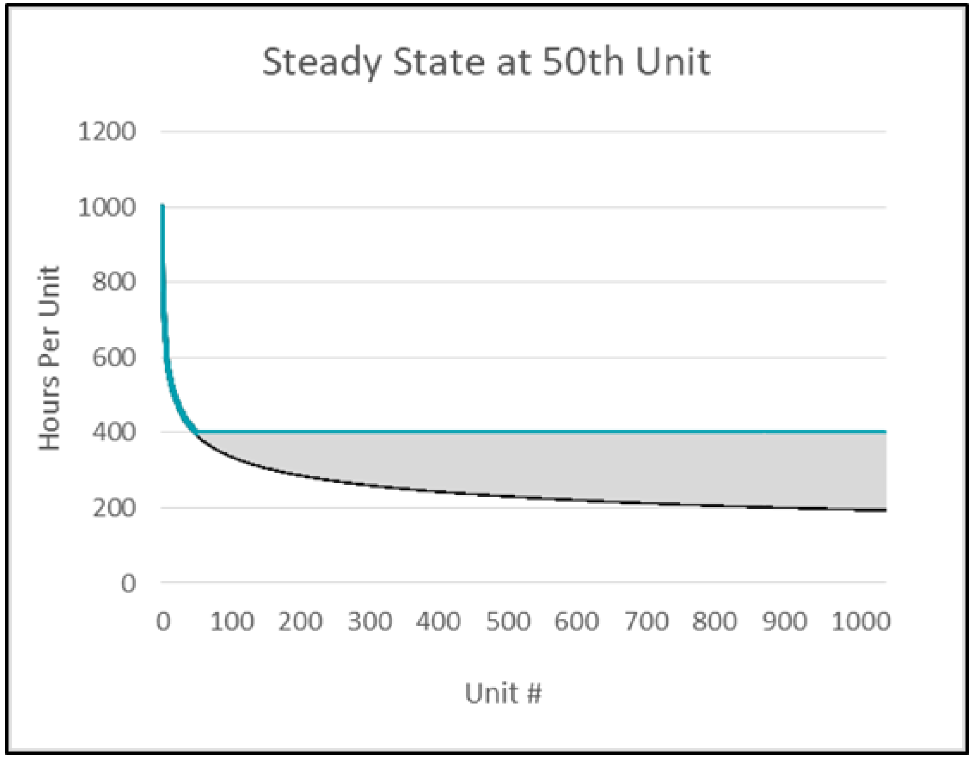
1. Konz, Stephan (1995). *Work Design: Industrial Ergonomics* (4th ed.) (pp. 447-450). Scottsdale, AZ: Holcomb Hathaway.

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

- Avoid underestimating direct labor hours:





Steady State Starting Unit	1,000	750	500	250	100	50
Total Hours Required	257,918	259,754	267,905	294,340	349,466	405,155
Difference in Hours Required	N/A	1,836	9,987	36,422	91,548	147,237
% Increase in Hours	N/A	0.7%	3.9%	14.1%	35.5%	57.1%

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**[2], 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**[2], 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

2. *Gagniuc, Paul A. (2017). Markov Chains: From Theory to Implementation and Experimentation. USA, NJ: John Wiley & Sons. pp. 46–59.* ISBN 978-1-119-38755-8

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"[3]

- 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

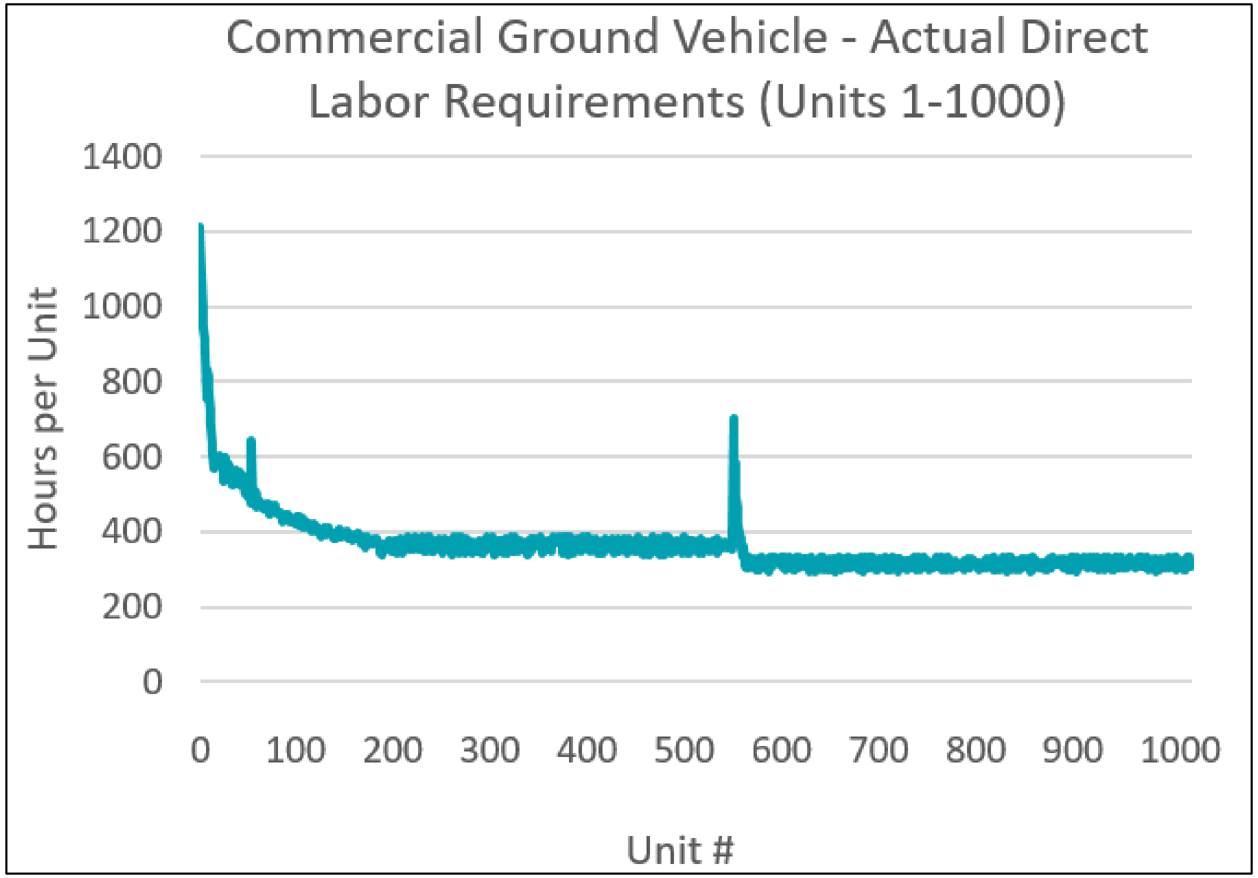
3. Hopp, Wallace J., Spearman, Mark L. (2000). *Factory Physics (2nd Ed.)*. New York, NY: McGraw-Hill

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

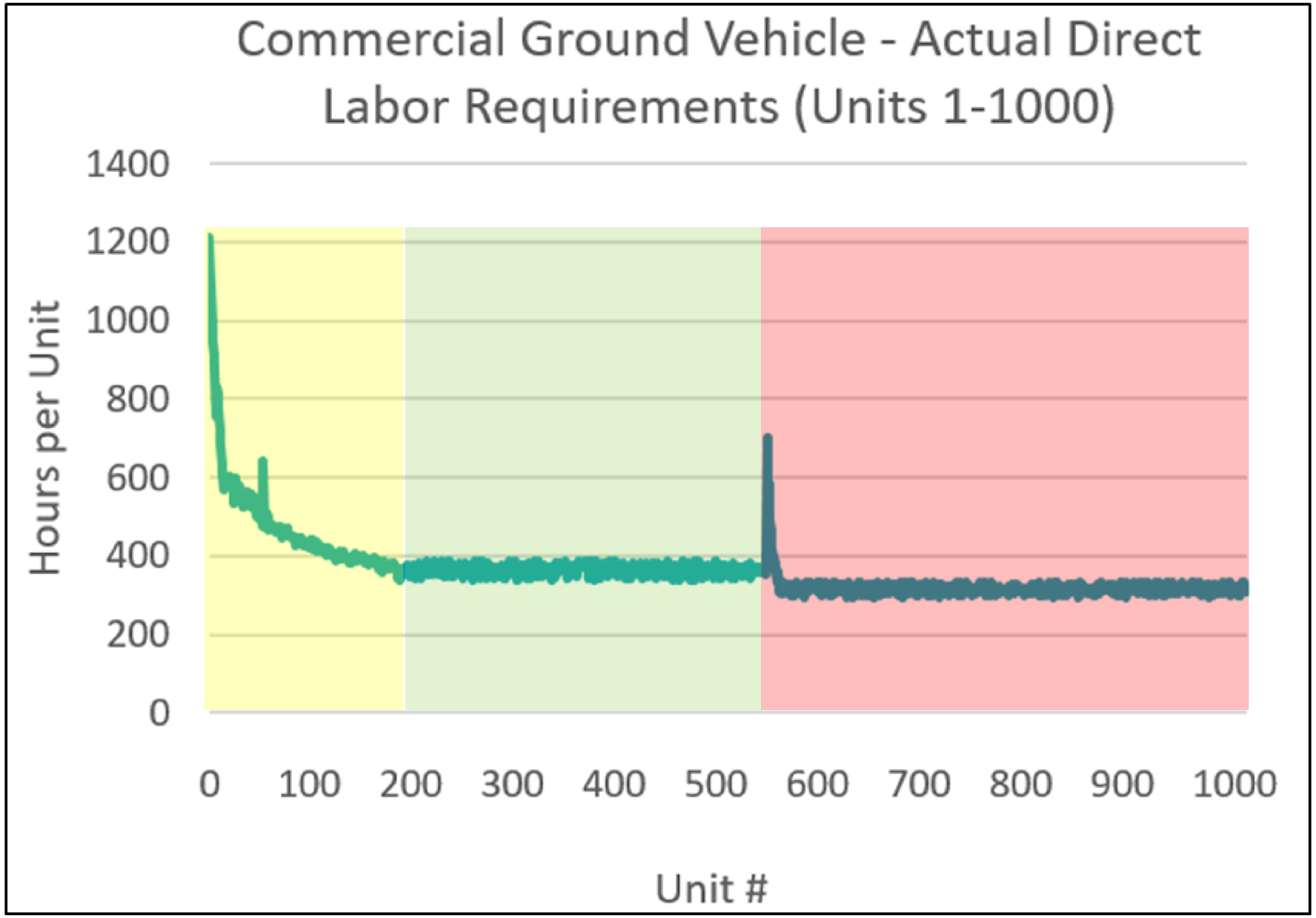
- System Overview
  - Plot of data for a commercial wheeled vehicle system with a BWS of 330.0 hours/unit
  - Interested in using this system to predict labor requirements for a new, comparable DoD system



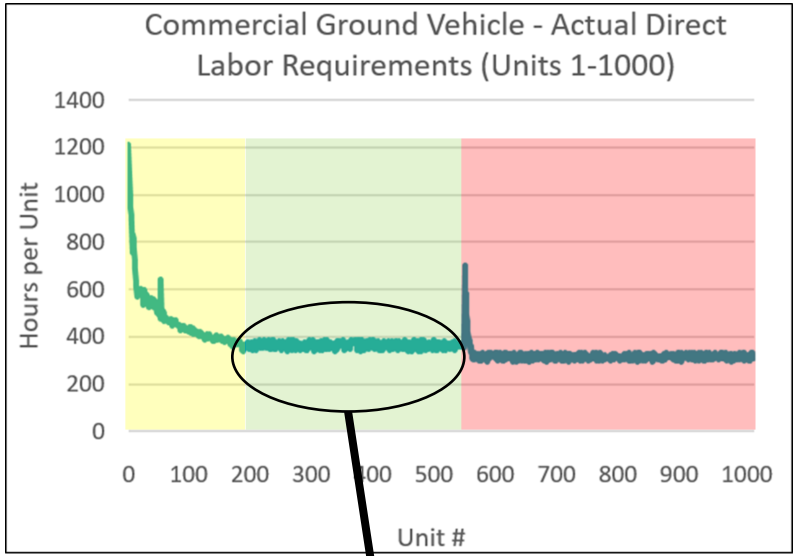
Example - Identifying the Steady State

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

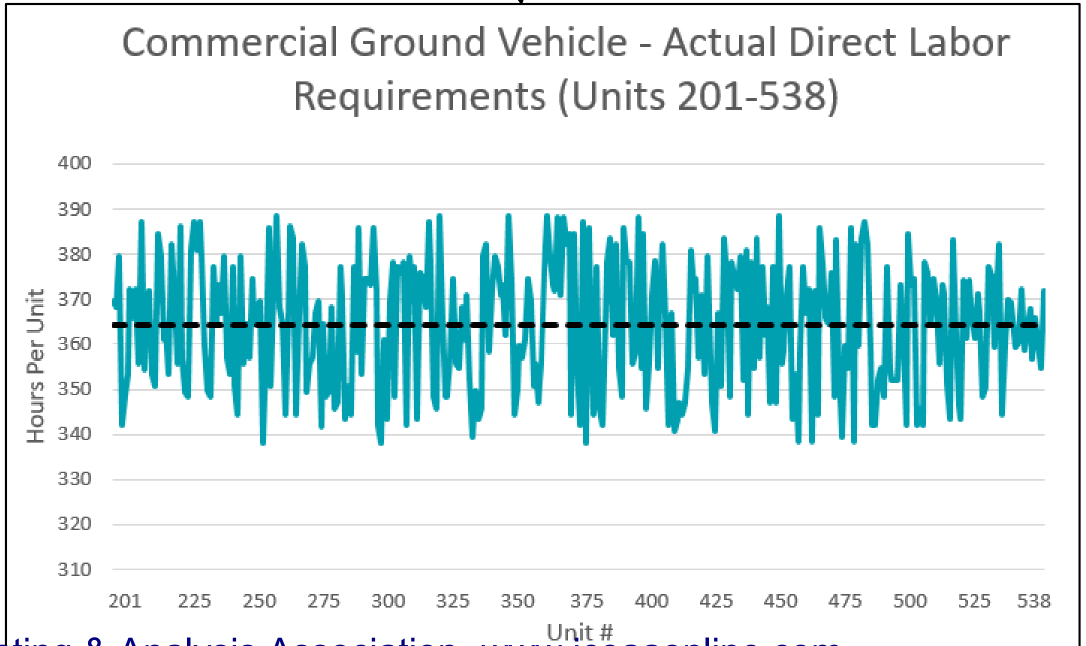


Example - Identifying the Steady State



Step 1a: Plot the Data

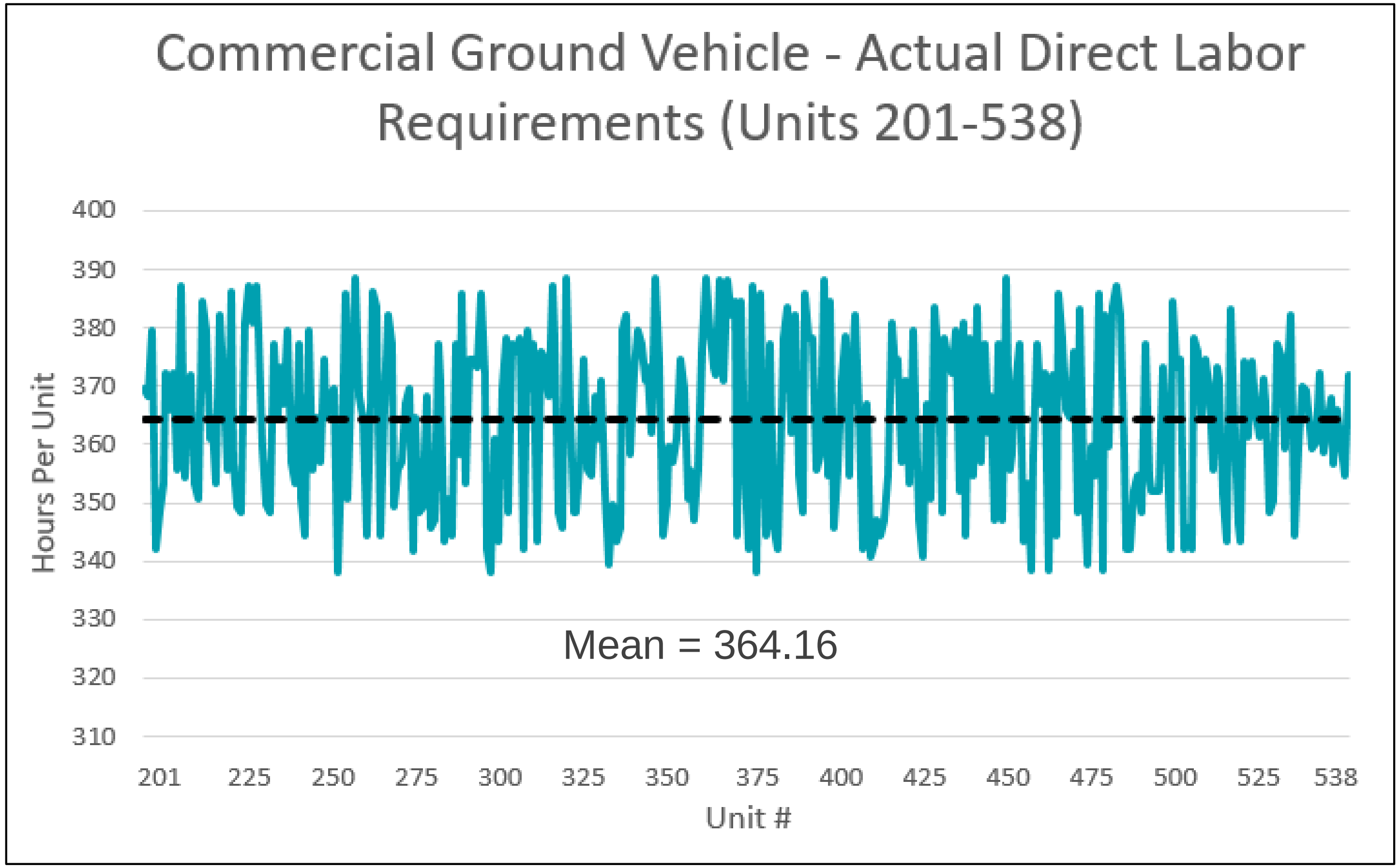
- Conclusion 1: Steady state appears to occur between units 201 and 538
- Conclusion 2: Variability is clearly present in data set, but it does seem evenly distributed above and below the mean without any obvious trends



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



	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Qty	34	34	34	34	34	34	34	34	34	32
Mean	367.02	364.50	361.69	363.42	368.00	365.32	363.43	363.10	361.69	363.35
Variance	187.22	182.90	211.49	228.38	203.02	258.02	197.80	252.73	212.64	96.73

Example - Identifying the Steady State

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 ε_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 β cannot be positive, however, we can't use the usual t test
- The coefficient follows a tau distribution. Testing tau statistic τ (which is equivalent to the usual t statistic) is less than τ_{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

Dickey Fuller Table

N \ α	0.01	0.025	0.05	0.10
25	-3.724	-3.318	-2.986	-2.633
50	-3.568	-3.213	-2.921	-2.599
100	-3.498	-3.164	-2.891	-2.582
250	-3.457	-3.136	-2.873	-2.573
500	-3.443	-3.127	-2.867	-2.570
>500	-3.434	-3.120	-2.863	-2.568

Example - Identifying the Steady State

Step 3: Statistical Testing

$\Delta y = y_n - y_{n-1}$

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

Perform Regression Analysis

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.703669
R Square	0.49515
Adjusted R Square	0.493643
Standard Error	14.26107
Observations	337

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	66822.47991	66822.48	328.5629	1.1754E-51
Residual	335	68131.63537	203.378		
Total	336	134954.1153			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	360.6892	19.91345053	18.11284	1.33E-51
X Variable 1	-0.99052	0.054645335	**-18.1263**	1.18E-51

Compare τ statistic w/ Critical Values

Dickey Fuller Table

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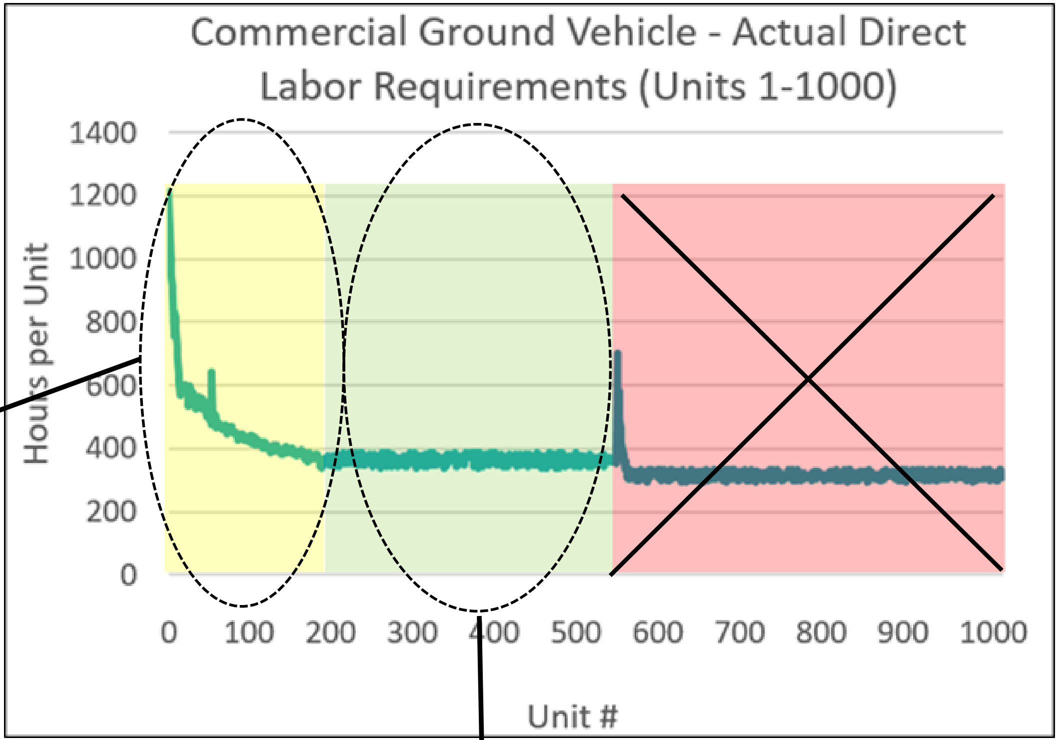
Conclusion

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

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

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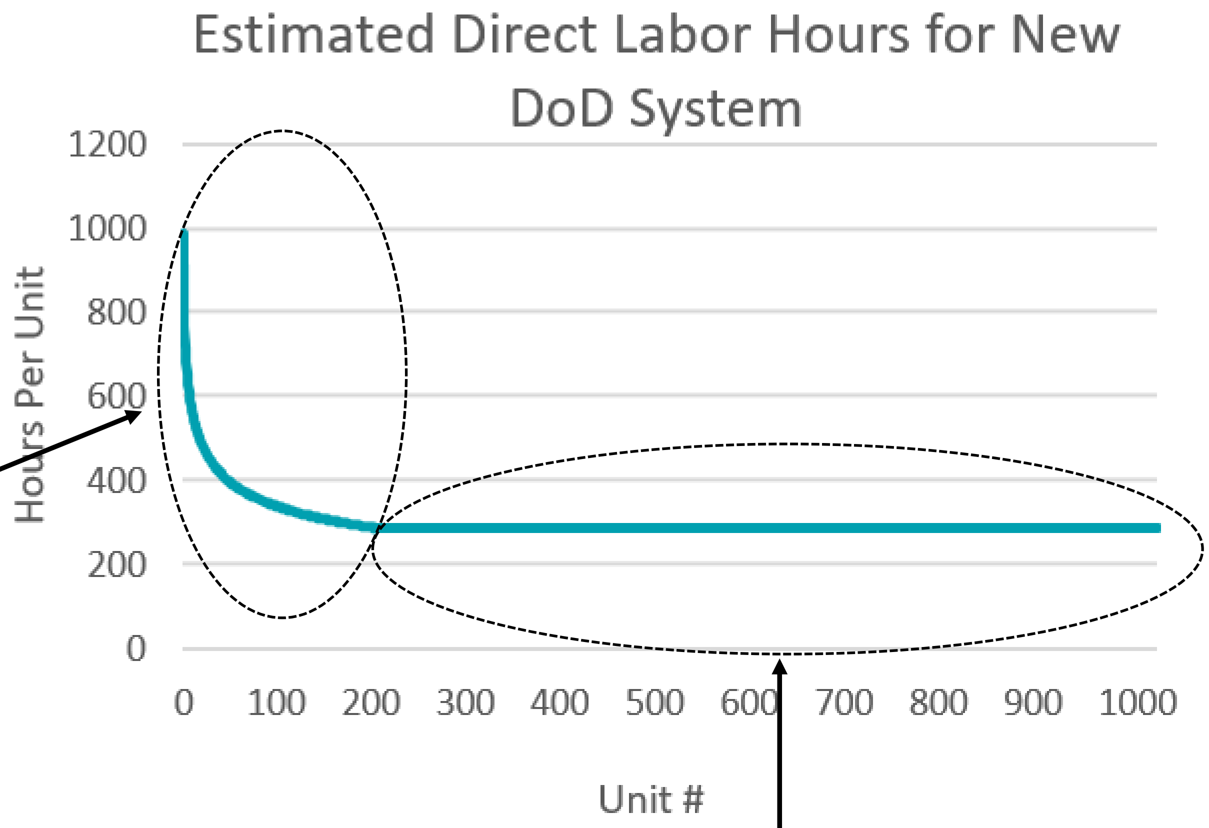


$Y = 990.3 * X^{-0.234}$

For Units 1-200

Since $285.6 = T_1 * 201^{-0.234}$,

$\mathbf{T_1 = 990.3}$

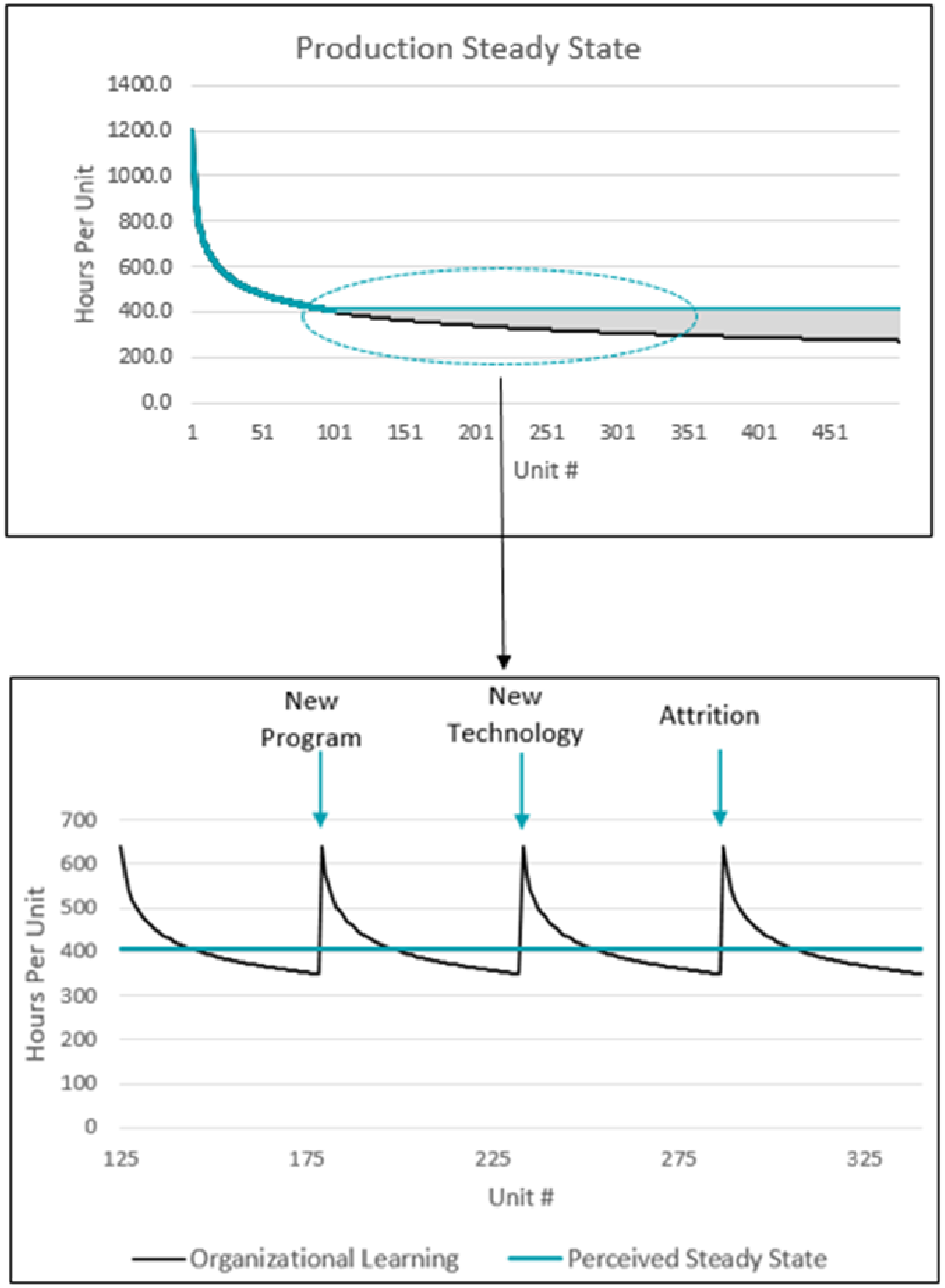
HPU_{SS} = BWS/Efficiency

= 258.75/0.906 = **285.6 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

Q&A

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