NATIONAL RECONNAISSANCE OFFICE

Developing Space Hardware Box NR CERs at the NRO CAAG

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SUPRA ET ULTRA

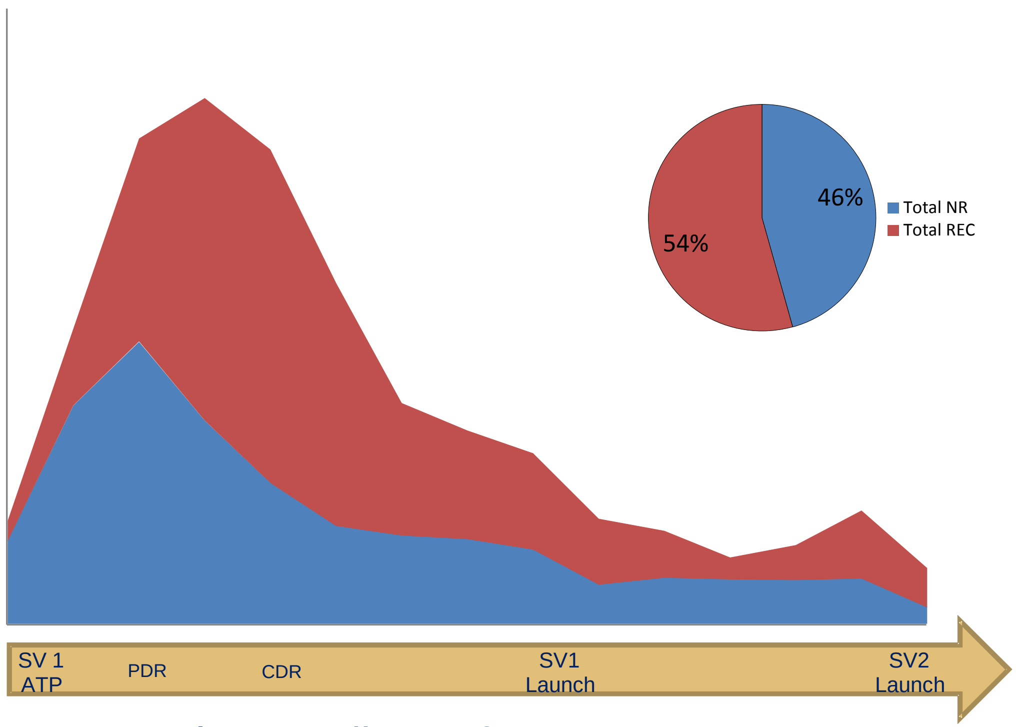
About the NRO

- The National Reconnaissance Office (NRO) is:
  - The national program to meet the U.S. Government's intelligence needs through spaceborne reconnaissance
  - A Department of Defense (DoD) agency and an element of the Intelligence Community
  - Funded through the National Intelligence Program and the Military Intelligence Program portions of the federal budget
- The NRO's existence was declassified by the Deputy Secretary of Defense on September 18, 1992

Agenda

- Background:
  - Nonrecurring Cost
  - Box-level estimates
  - CAAG Data Set
  - Equipment Groups
  - CER Development
- NRO CAAG NR CER Strategies
  - Selecting cost drivers
  - Segregating cost of NR engineering effort from cost of development units
  - Low % New Design values and Incidental Nonrecurring
  - Selecting the best CER

Nonrecurring Costs are Important



Actual Expenditures for NRO SV program

Nonrecurring Costs:
Requirements definition
Engineering design & analysis
Manufacturing tooling
Development units
Simulators
Development and acceptance test procedures
Redesign, rework & retest to correct design flaws

Recurring Costs:
Production unit parts & materials
Production unit fabrication, assembly & testing
Spare parts production units
Rework due to workmanship problems

Nonrecurring cost happens…

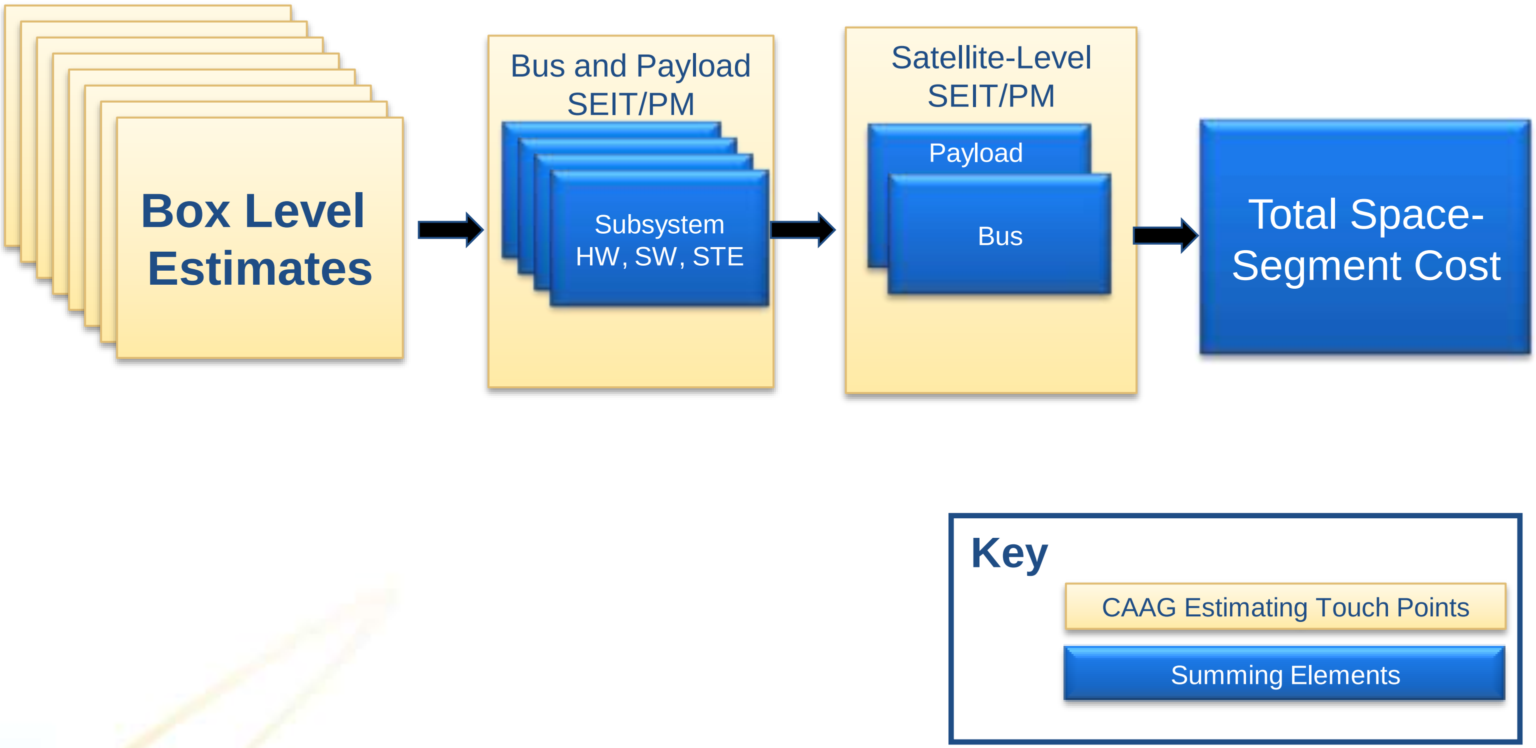
- For initial design, or upgrades and changes
- To address obsolescence in existing designs
- Or, even when there is no new design – “Incidental Nonrecurring”

NR costs can be a significant portion of total SV acquisition costs

Why are NR CERs Harder to Develop?

- Less data available for NR CER development than REC CERs
  - All units have recurring cost but not all units have significant NR cost
  - Not all organizations collect data on NRO CAAG preferred cost drivers
- More variance in the data, more “noise” around relationships and trends
- Difficulties in accounting for development units
- Intuitively, there are more cost drivers in play

NRO CAAG Estimates at the Product/Box Level



Why Box-Level Parametric Estimates?

Box Level

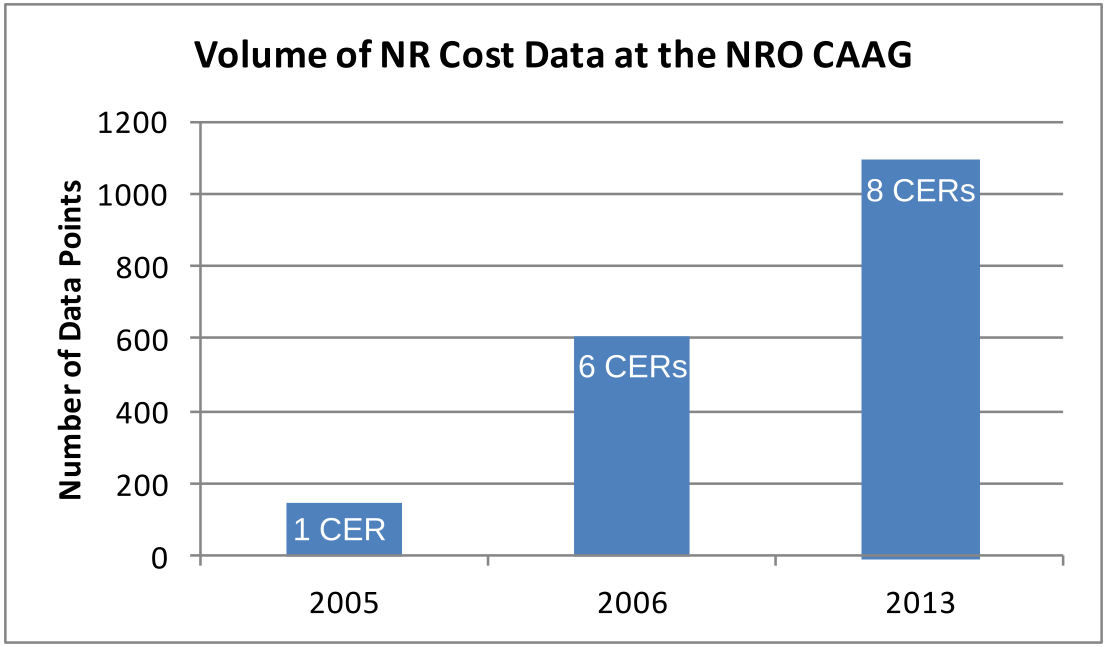
- Low enough level to:
  - Support design trades
  - Demonstrate detailed understanding of space vehicle
  - “Tune” the cost estimate to the technical baseline
- High enough level to:
  - Leverage collected data aligned to Standard Work Breakdown Structure
  - Incorporate lowest levels of SEITPM

Parametric

- Unbiased (Statistically)
- Repeatable
- Provides statistically quantifiable uncertainty
- Conducive to sensitivity and affordability analysis

Provides the most utility to support acquisition decisions and program execution

The Data Set



- The NRO CAAG has a lot of data, from many programs, and multiple sources
  - Disciplined data collection and participation with our industry partners has increased the volume of available cost data in recent years
- A larger and more updated data set is the primary reason to update our models – more data is a great thing
  - Better breakouts by equipment type, validation of trends, additional drivers are possible with more data

*counts only data with NR cost >0, and %new design > 0. Full data volume is closer to 2300 data points.

NRO CAAG Product/Box Level CER Inventory

8 Nonrecurring CERs

- RF Equipment
- Digital Equipment
- Antennas and Feeds
- Misc. Electrical / Electronics
- Structures and Mechanical
- Wheels, Drives, & Positioners
- ACS Sensors
- Optical

~80 Recurring CERs

Att. Control Elex (ACE)	Helix antenna	Solid Rocket Motors
Back-End RF Electronics	Dipole/Other antenna	Solid-State Transponders
Power Monitors	Nutation Dampers	Solid-State Transmitters
BAPTAs	Comm Data Processing Electronics	Star Trackers
Li batteries	Mission Payload Processing Elex.	Solar-Array Booms
NiCd batteries	Positioner assemblies	Other Deployable Structure
NiH batteries	Positioner motors	Secondary Structures
Booster Adapters	DC power converters	Trusses and Towers
Command Receivers	AC power converters	Equipment Compartments
GPS Digital	Phased Array Antennas	Optical Payload structures
Comm Front-End RF Electronics	Power & Coax Harnesses	Analog sun sensors
Comm LNAs	Propulsion Plumbing	Digital sun sensors
DC Power Harnesses	Pressurant Tanks	Bus and RF Payload thermal H/W
Deployment Drives	Propellant Tanks	EO Payload Thermal H/W
Driver Control & Data Routing Elex	Pyro Driver Electronics	Thermal Shields/ Barriers /Louvers
Earth Sensors	RF Coax Harnesses	Thermal Heaters and Sensors
EPS Electronics	Shunts, Dissipators and Capcitors	Thermal Heat Pipes & Radiators
Flight Computers	Feeds	Thermal Blankets
IRUs	Front End RF Electronics	Thrusters
Accelerometers	Preamplifiers	Oscillators
Large Deployable Reflectors	Small Parabolic Antennas	Timers/Clocks
Magnetic Torquers	GaAs, deployable arrays	TT&C Digital Electronics
Magnetometers	GaAs, not deployable arrays	TWTAs
Downlink MW Plumbing	Silicon, deployable arrays	Waveguide Assemblies
TT&C MW Plumbing	Silicon, not deployable arrays	Reaction Wheels
Horn antenna	Solar Array Drives	CMGs
Spiral antenna		etc.

- There are recurring CERs for most Space Hardware Equipment Groups, there are far fewer nonrecurring CERs

Grouping the Equipment Types

1) RF Equipment
Receivers
Transmitters
Transponders
Up/downconverters
Modulators
Oscillators
Power Divider/Switching Units
LNAs
SSPAs
TWTAs
Laser Sources
Analog signal processors and readouts
Coax harness
Microwave plumbing

2) Digital Electronics
Payload digital processing and control
Encoders/decoders
Command units
Telemetry units
Flight computers
Solid-state recorders
AD and DA converters
Digital multiplexers
Encryption/Decryption units

3) Antennas and Feeds
Reflectors
Feeds (all types)
Antennas (all types)

4) Misc. Electrical/ Electronic
Valve drivers
Heater controllers
Pyro/squib drivers
Battery controllers
Batteries
Solar arrays
Solar-array regulators
ACS electronics
Servo electronics
Power converters and conditioning
Payload power supplies
Power harness
Magnetic Torquers

5) Structure and Mechanical
Thrusters
Tanks
Propulsion plumbing
Structure
Booms
Thermal blankets
Heat pipes
Radiators
Paints
Tapes
Louvers
Cold plates
Sensor mounts
Optical benches
Outer barrel assemblies
Optical baffles
Nutation Dampers
Booster Adapters

6) Wheels, Drives, & Positioners
Positioners
Deployment drives
Gimbals
Wheel devices
Actuators
Solar array drives

7) ACS Sensors
IRUs
Sun sensors
Star Trackers
Earth Sensors
Accelerometers
Magnetometers

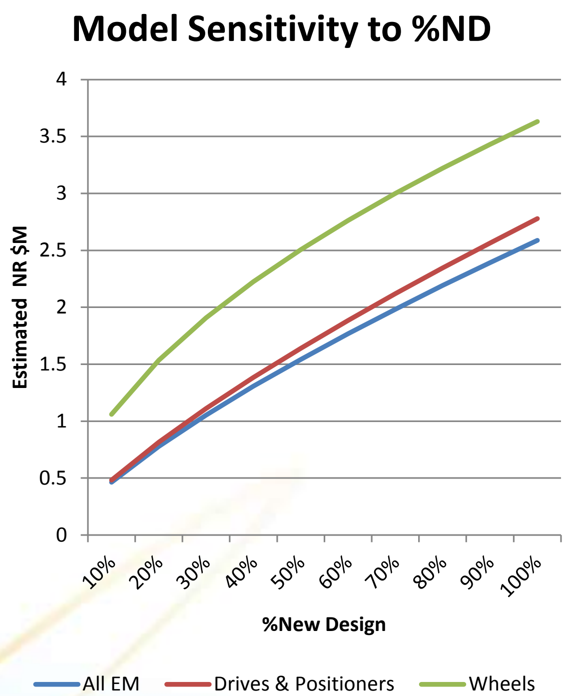
8) Optical
Mirrors
Lenses
Telescope assemblies
Optical Filters/Grates/Prisms

- Groups should be small enough to have a similar response to NR cost drivers yet large enough to capture sufficient data points

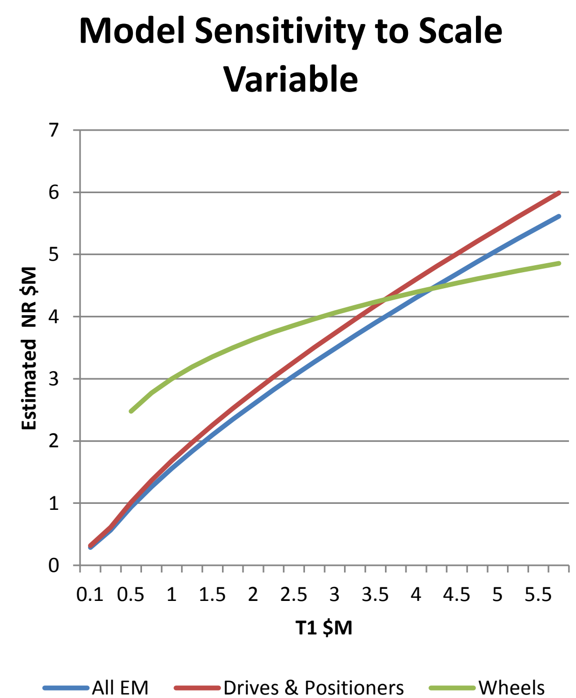
Equipment Type Stratification

- When multiple equipment types are grouped into one data set we can use dummy variables to stratify a CER based on subgroups
- Models must have similar behavior over the range of expected values for both scale and complexity variables

Good



Bad

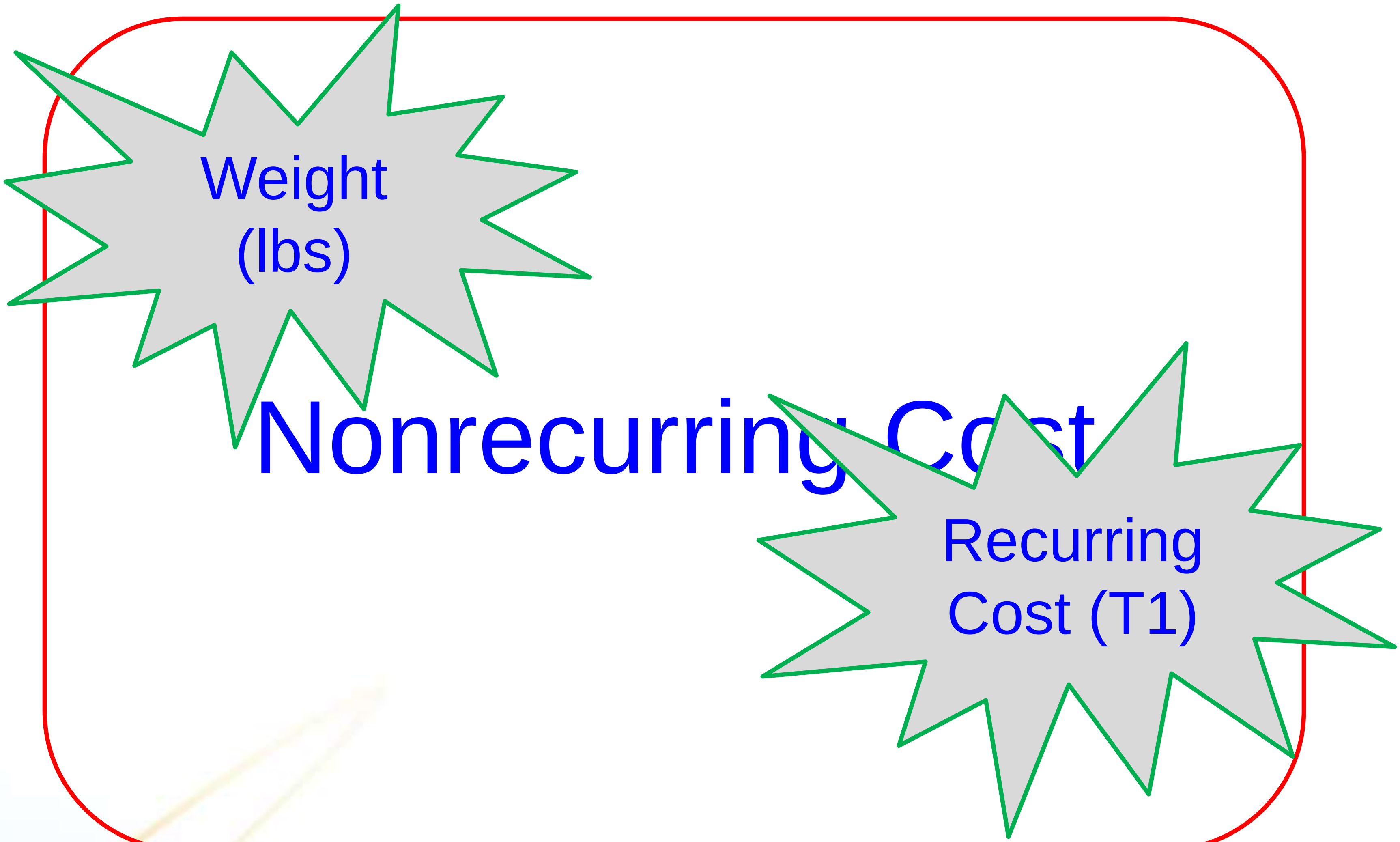


$$NR = a(T1)^b (Qty)^c (\%ND)^d e^{drives} f^{wheels}$$

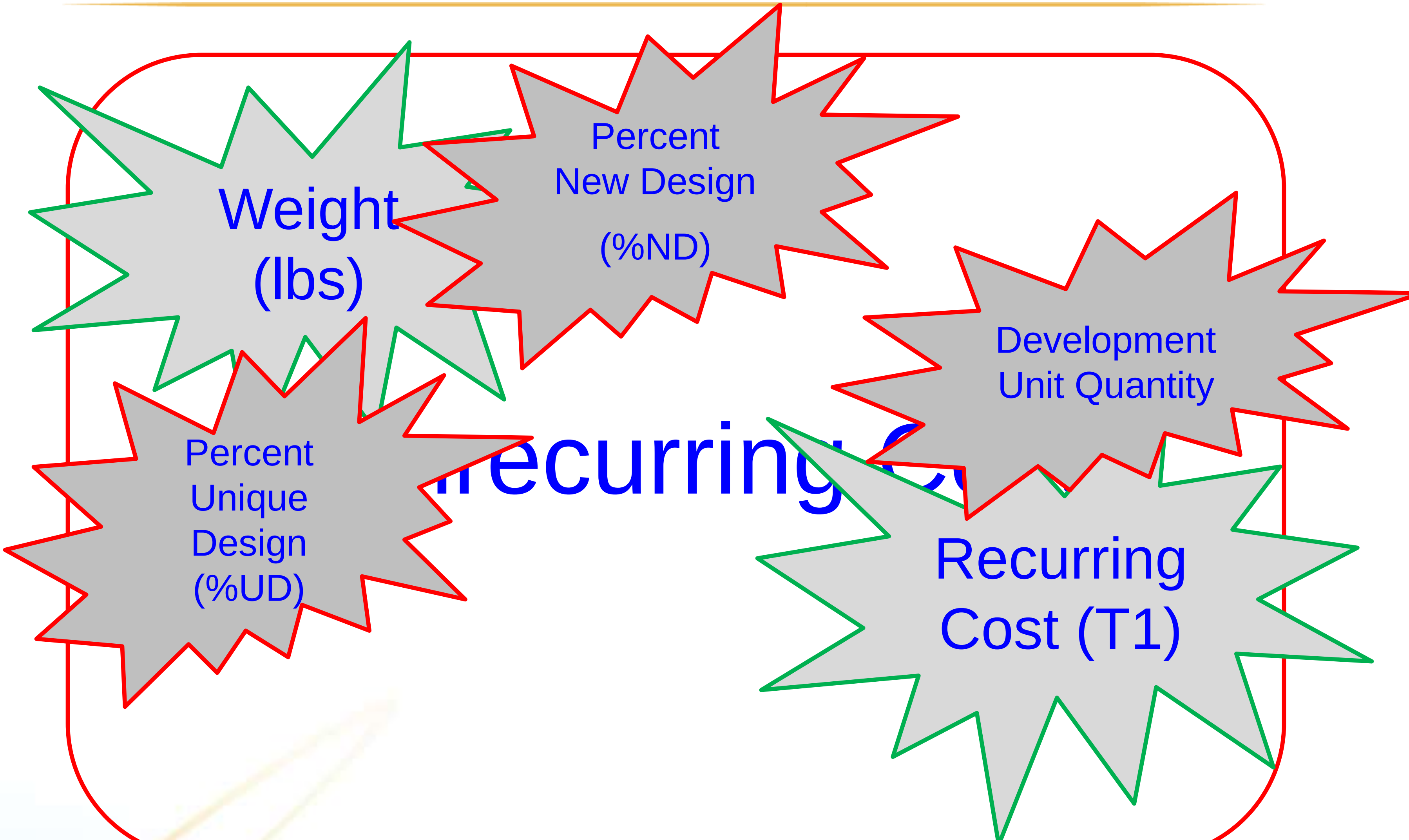
Drivers of NR Cost

Nonrecurring Cost

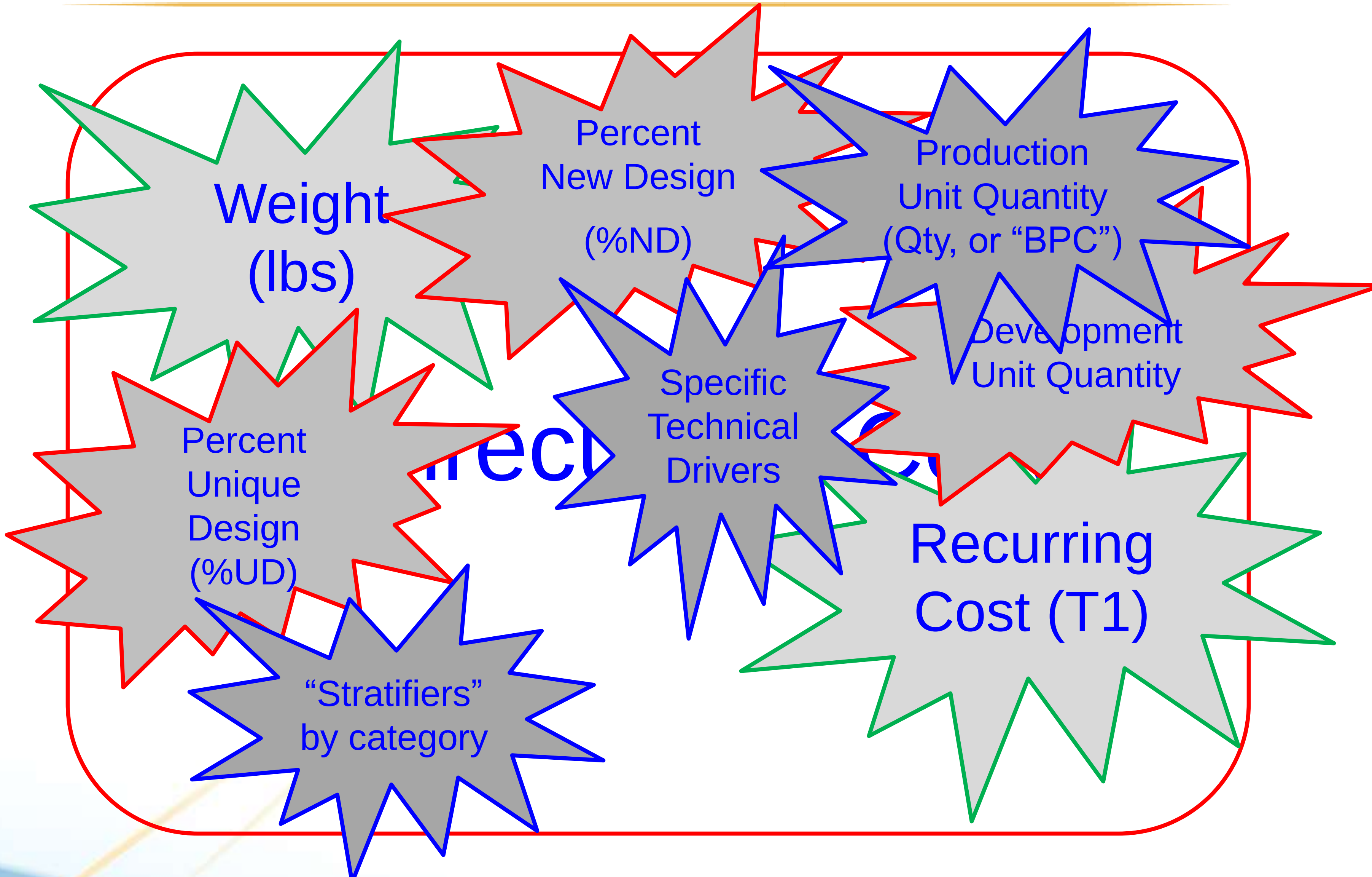
Drivers of NR Cost



Drivers of NR Cost



Drivers of NR Cost



NR CER Functional Forms

Typical CER forms:

$$\$NR = a\,Scale^{b}\,Complexity_{1..n}^{c_{1..n}}$$

$$\$NR_{eng} = a\,Scale^{b}\,Complexity_{1..n}^{c_{1..n}}$$

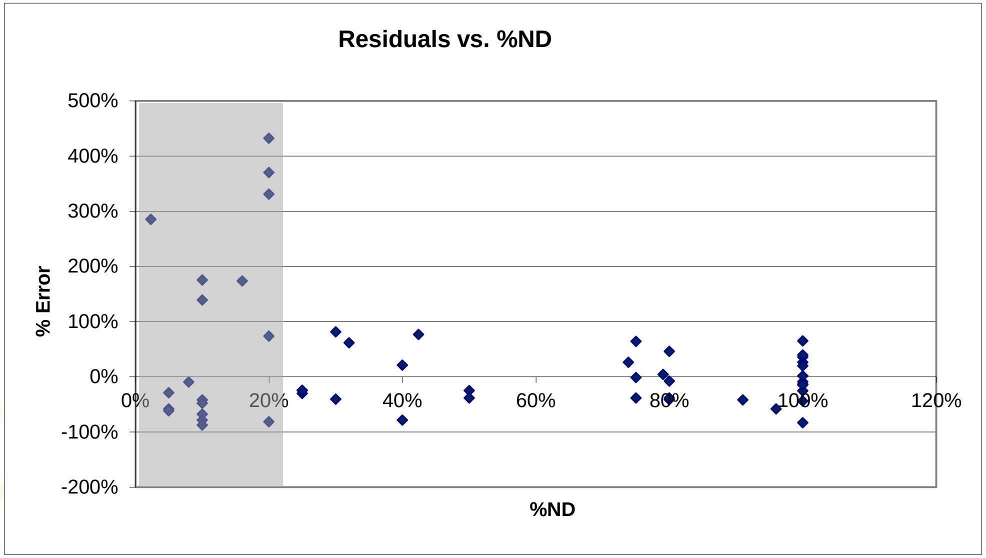
- What is Nonrecurring Engineering (NReng)?

$NR_{total} = NR_{eng} + NR_{H}$ so… $NR_{eng} = NR_{total} - NR_{H}$

- NR_H is derived under some rule-of-thumb assumptions:
  - NR Hardware cost is a multiple of the recurring cost of a unit
    - NR_H = T1*(development unit quantity)
  - …and we can simply count those development units like this:
    - An EM counts as half a unit
    - A TQ counts as a full unit

Estimating for Low %ND Boxes

- Very low %ND points can be very small and create large errors on a percentage basis and have a significant impact on regression coefficients due to their increased dispersion
- High dispersion in costs for low %ND points causes CER summary statistics to overstate estimating uncertainty for the high value points
- All else being equal, points with high %ND are more expensive and are more important to estimate accurately



$$\$\,\mathrm{NR} = \mathrm{a}\, T1^{b}\, \%ND^{c}$$

Incidental Nonrecurring (INR) Costs

- Some boxes with 0%ND have nonrecurring costs, we call this INR
  - Boxes without new design are common in follow-on vehicles
  - Caused by a variety of factors: product improvement, minor obsolescence, startup admin, mfg setup, analysis for use in new environments, requal, etc.
- Inputs with 0%ND would always result in an estimate of zero costs in our standard multiplicative functional form
- In order to capture INR costs, alternative models were attempted for each equipment type

$$\mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND} + \mathrm{c})^{\mathrm{d}} \qquad \mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND})^{\mathrm{c}} + d(T1)$$

$$\mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND} + .05)^{\mathrm{d}}$$

Despite attempts, we recommended continued use of a separate INR model for all equipment groups instead of box specific models

Low %ND Values Solution

- Analysts attempted clipping the data set to remove low %ND values
  - Improved reasonableness of coefficient values
  - Improved performance metrics
  - Maintained sufficient degrees of freedom
- The %ND threshold for clipping was determined by performing sensitivity analysis and finding a knee in the curve with diminishing SPE and R2 improvements

Model	%ND	DOF	SPE	R^2
1	>0	62	95.4%	37.3%
2	0.1	57	77.0%	36.6%
3	0.15	50	67.6%	25.2%
4	0.2	49	67.8%	23.0%
5	0.25	45	57.6%	49.8%
6	0.3	40	56.3%	50.8%
7	0.5	33	59.2%	56.3%

%ND as a categorical variable

- %ND values require engineering judgment and are difficult to calculate accurately
- A categorical variable for %ND would have some benefits
  - Makes more data available for analysis
  - Alleviates lower bound issues
  - Simplifies data collection requirements

Example Categories

%ND Category Grouping	%ND Range
Minor Modification	0-30
Moderate Modficiation	30-60
Significant Modification	60-90
Major Modification	>90

- Analysts attempted CER models with this strategy, with mixed results

We continue to use %ND as a continuous variable, but we will explore this strategy further in future studies and CER updates

EVALUATING REGRESSION RESULTS

Pick a Winner

- So, you've generated 120 CER candidates from your data set using multiple regression analysis methods… which will you recommend?

Criteria for choosing the "best" CER

- Consistency with technical evaluation and engineering knowledge
  - Exhibited cost relationships agree with expectations
- Quality and performance metrics
  - SPE (lower is better)
  - Bias (lower is better, typically driven to zero)
  - Trends in residuals charts
- Other factors to consider
  - Degrees of freedom (more is better)
  - Quality of sample data
  - Applicability and Ease of Use
  - Sensitivity to influential data points

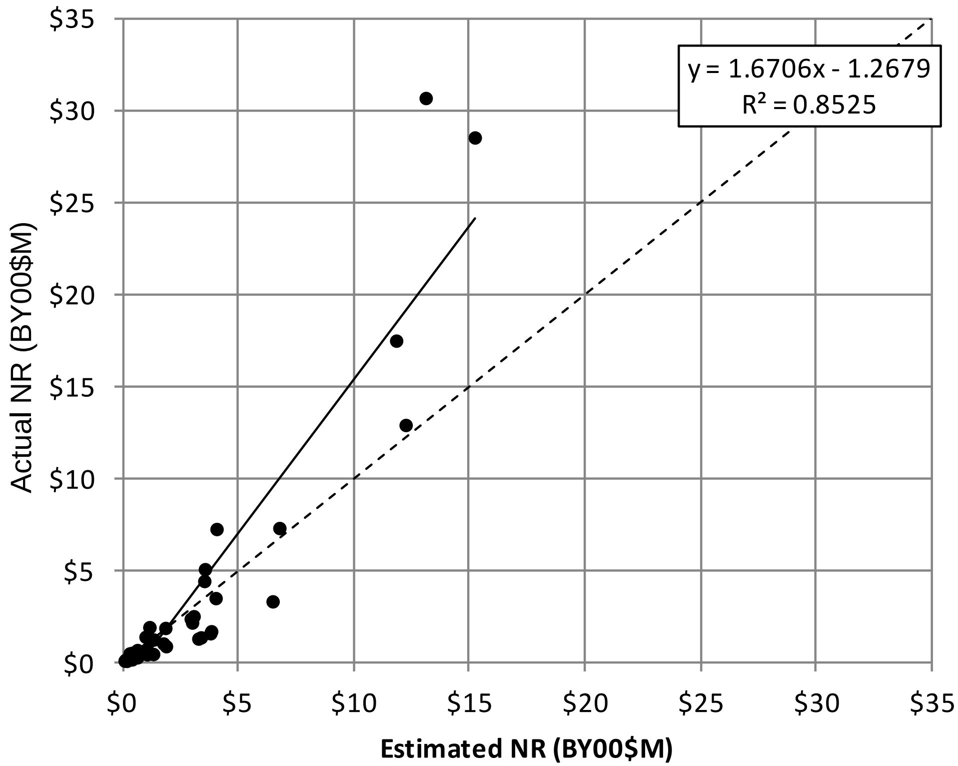
Cost and Acquisition Assessment Group

Also:

- Sensitivity to desired cost drivers
- Equipment "sub-groups:" - how well does the model estimate each *type* of HW
- Simplicity – lends to ease -of-use
- Residuals Analysis – watch out for trends in the errors (*slides to follow*)

Spotting the Trends

Actuals vs. Estimates



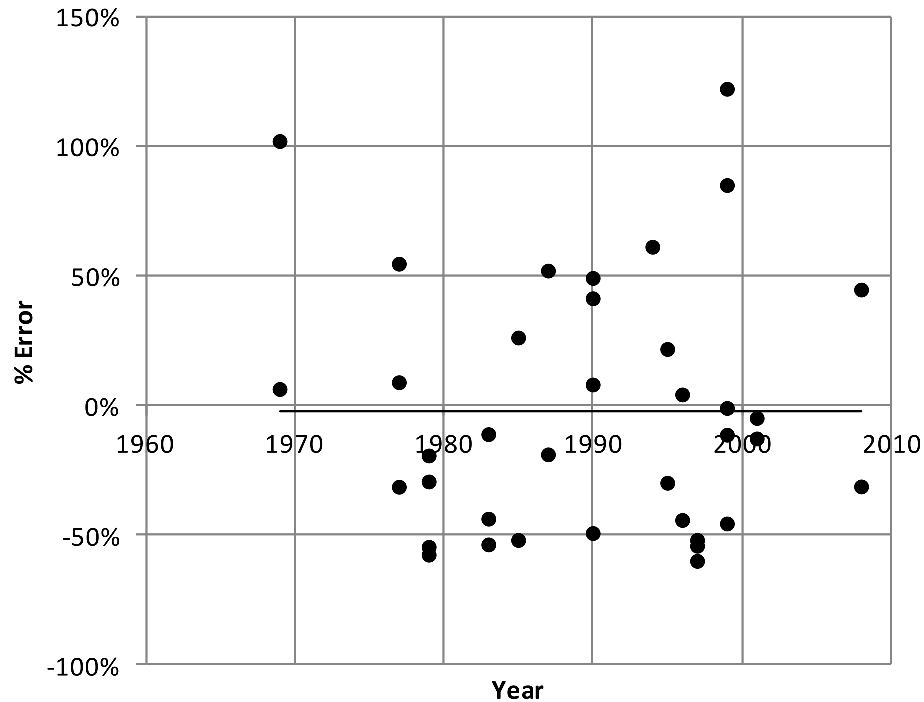
CER underestimates at the high end of the data set.

- Examine scatter plots of the resulting estimates to diagnose potential issues with a CER Candidate

Spotting the Trends
Residuals Analysis

CER underestimates these points.

CER overestimates these points.

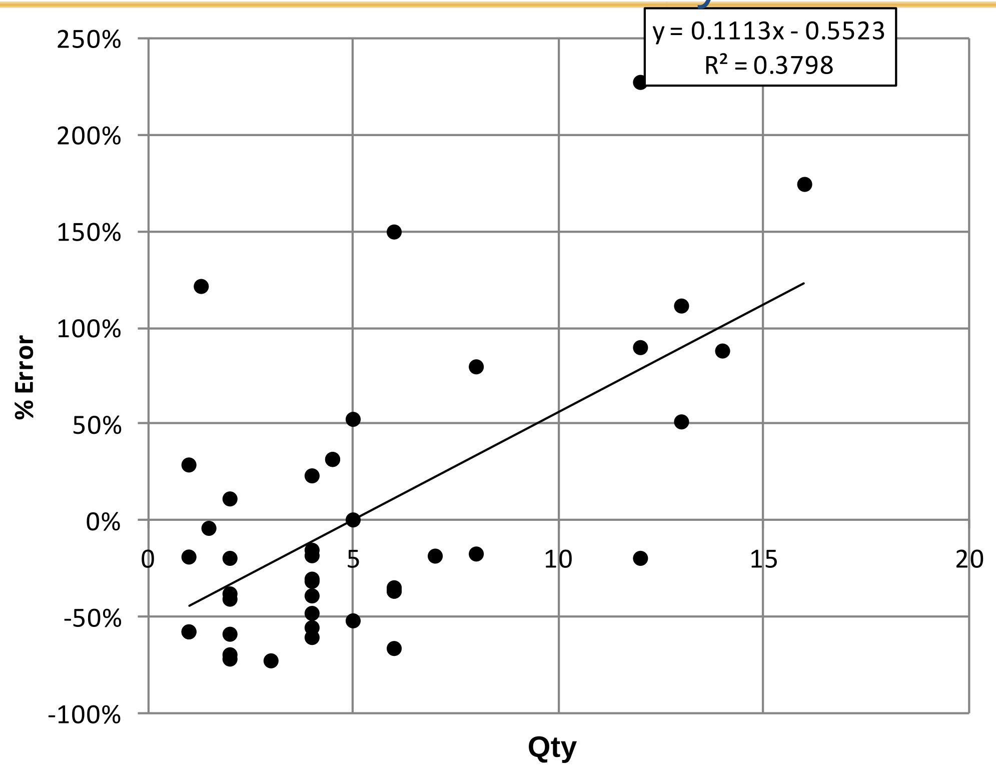


Residuals show no trending with time.

- Examine scatter plots of the errors against NR drivers both in unit space and log space
- Can help diagnose potential issues with:
  - CER candidates
  - Data quality

Spotting the Trends

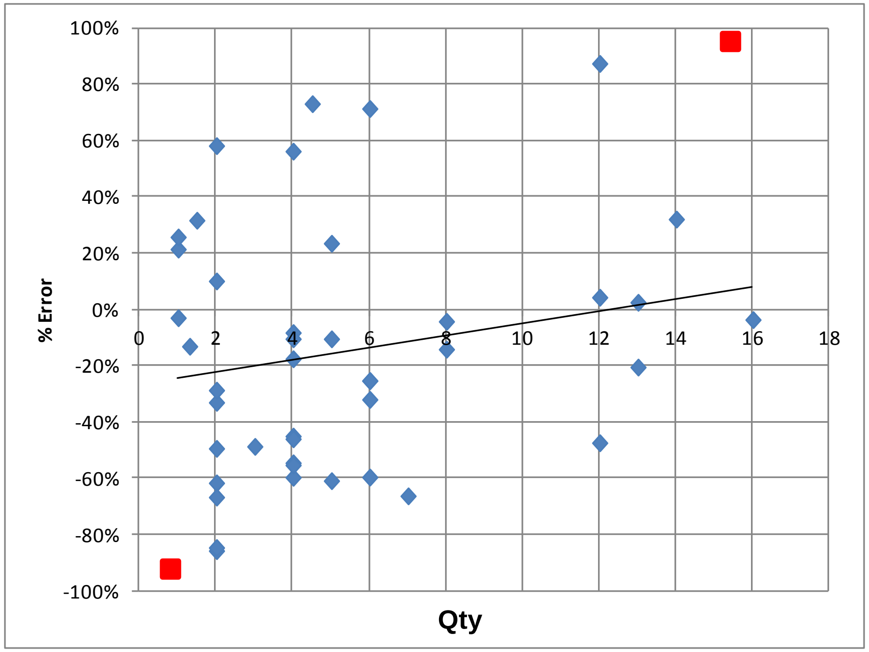
Residuals Analysis



Residuals show trending with production quantity, this CER may need to include this driver.

- An evident trend in the residuals can be an indication of a missed driver from the CER data set
- This model will likely perform better once production quantity is added as a cost driver

Search for "High Leverage" Outliers

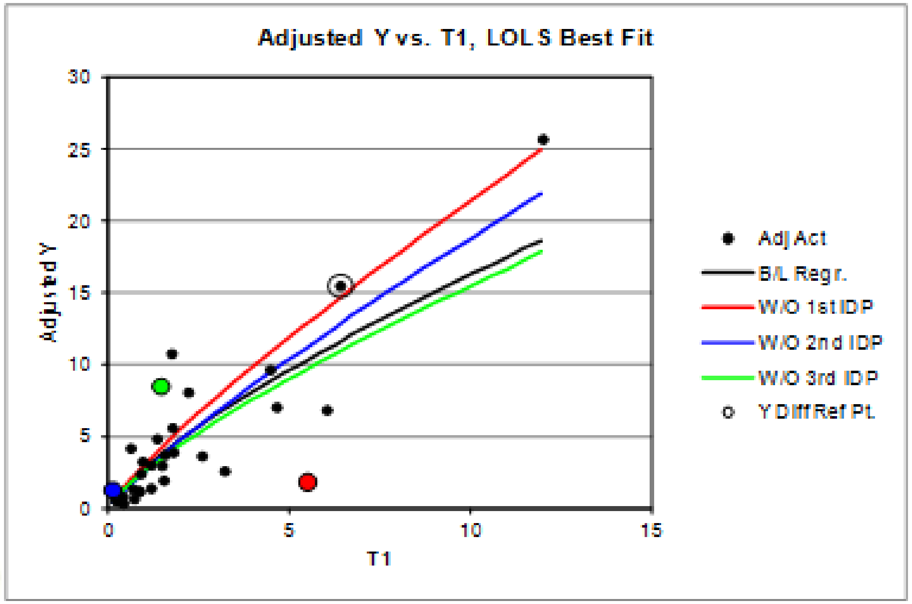


- In the case that an exponent is unexpectedly high, look for high leverage outliers that are driving the exponent up
- Omitting just one outlier can cause a significant change – *and one or two data points should not determine the trend !*

CER Analysis Tool (CERAT)

Searching for Influential Data Points

- The outlier data points that really matter to us are those that are "influential" to our CER results, or its resulting coefficient values
- The CER Analysis Tool searches for influential data points (IDPs) by iteratively removing one point at a time and re-running the regression, tabulating and plotting results



- Obvious outlier data points are not always IDPs, and vice-versa
- IDPs are not automatically omitted, it's up to the analyst to decide

*Image from D. Mackenzie, ISPA-SCEA presentation on IDPs – Feb 2012

Summary

- Group data from multiple equipment types to mitigate issues caused by a small data set but watch the trending against drivers
- Watch out for data points with very small values (cost or scale) and consider omitting these points
- Screen CER candidates for reasonable coefficient values and satisfactory quality metrics
- Evaluate residual trending vs. all cost drivers, stratifiers and other related parameters
- Search for overly influential data points

Questions?

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