NASA Project Cost Estimating Capability: New Analyses for Spacecraft Estimating

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Engineering Cost Office

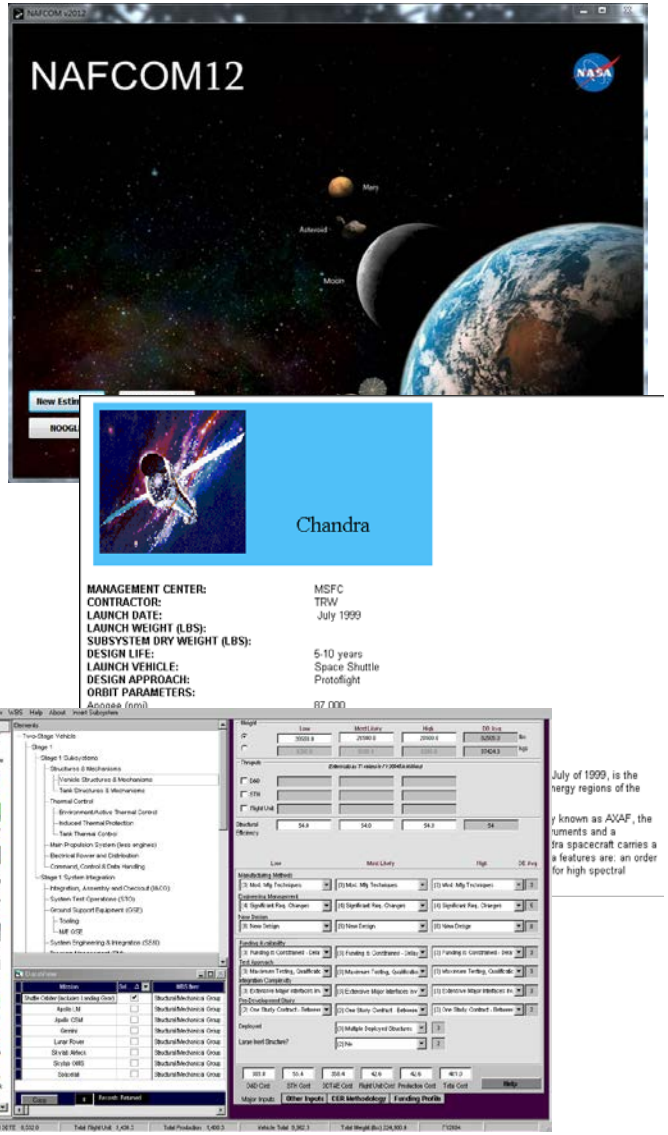
Overview

- NASA / Air Force Cost Model (NAFCOM) History
- Project Cost Estimating Capability (PCEC) Introduction
- PCEC Analysis Approach
  - Robotic SC
  - Crewed and Space Transportation Systems
- PCEC Capabilities
- Summary

NAFCOM History

NAFCOM Overview

- **Overview**
  - Parametric cost estimating tool for launch vehicles, robotic spacecraft, human spacecraft, landers, rovers, and other flight hardware systems
  - Development began in 1990 with 12 major releases providing increased accuracy, data content, & functionality
  - Based on over 155 NASA and U.S. Air Force space flight hardware projects
  - Used by over 1000 Government and Contractor employees
  - Two cost estimating methodologies are available:
    - Multi-Variable CERs
    - Weight/Analogy based CERs
  - Incorporates Liquid Rocket Engine Cost Model (LRECM) and Space Operations Cost Mode (SOCM)
  - Allows user input CERs and thruput costs
  - Performs probabilistic risk analysis using FRISK
- **Versions of NAFCOM**
  - **Government:** Includes modeling capability and access to all underlying data
  - **Contractor:** Includes Government version capability (CERs, etc) but no underlying cost & mass data



NAFCOM Over the Years

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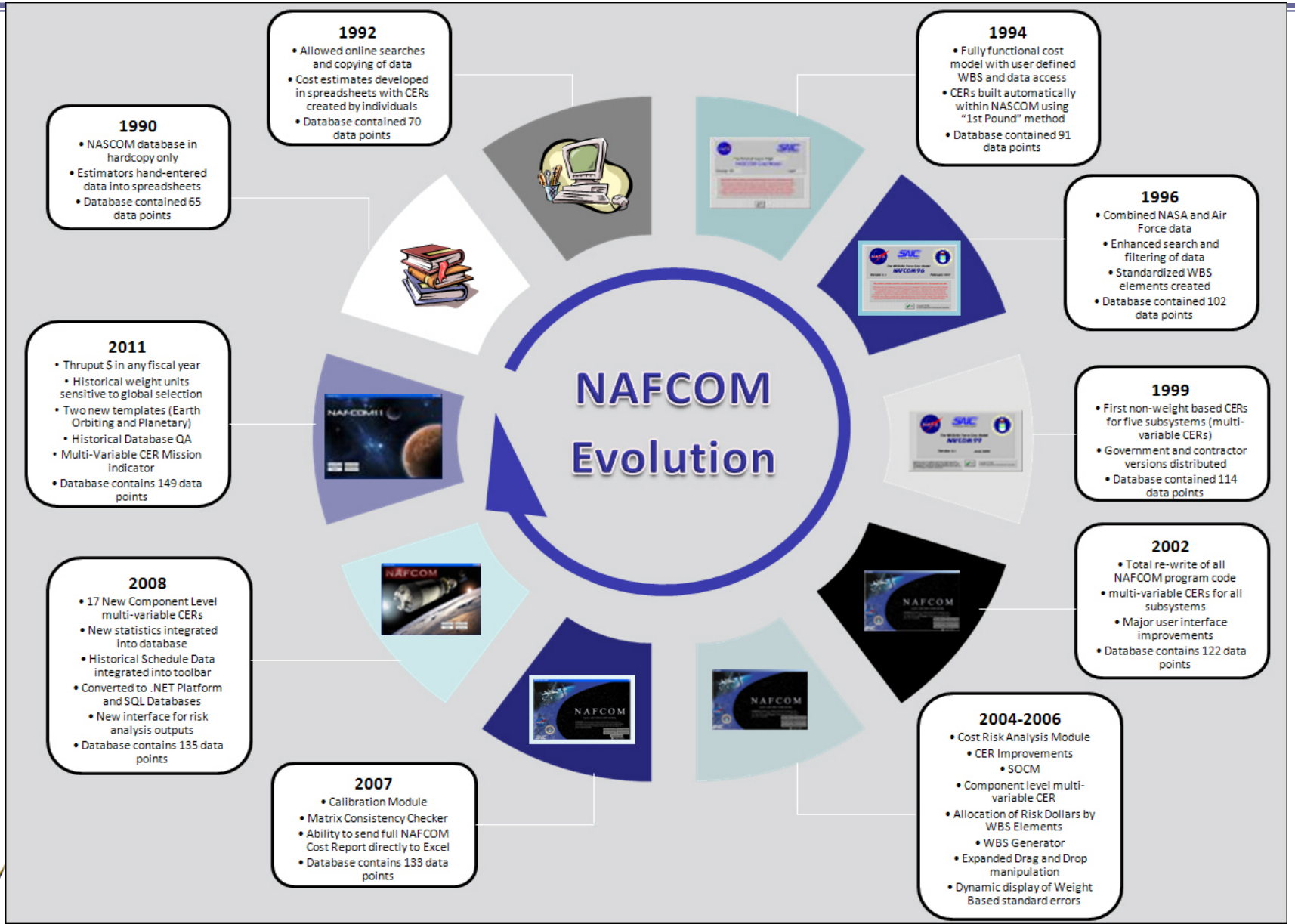

Why Move Away from NAFCOM?

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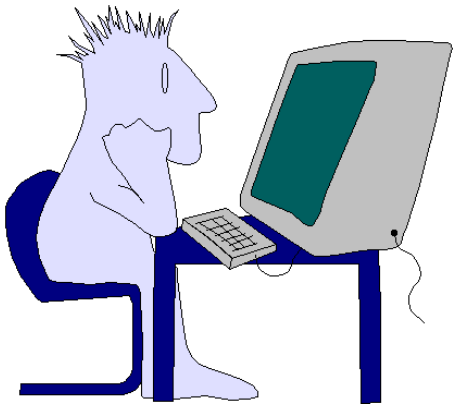
- **CER Issues**
  - Non-Homogeneous data set
  - Input parameters that are statistically insignificant
  - Subjective variables have significant explanatory value
  - Documentation for assigning subjective variables limited
  - Oversubscribed CERs
  - Some CERs yield nonsensical results
- **Software Issues**
  - “Black box” to users
  - Calculation errors
  - Data protection requirements
- **Analysis Issues**
  - Results produced in standalone environment
  - Over-reliance on exercising the model

Moving to a Data Centric Approach



Model Centric

- Focus is on how to use the model
- Model becomes a medium for communication with the technical community
- Model gets all the credit (or blame) for the estimate
- **Estimate becomes an evaluation of the present, rather than a prediction of the future**

Data Centric

- Focus is on the relationship of the data to the estimating problem
- Analyst must access and know the underlying data
- Puts onus for the quality of the estimate on the estimator
- **Done properly, can lead to value-added solutions**

PCEC Introduction

What is PCEC?

- PCEC is a new parametric cost model developed and maintained by NASA to replace NAFCOM
  - PCEC development started in late 2013 to begin a new course for space cost estimating, leveraging the historical analyses but expanding them to align with evolving NASA estimating needs

- Goals for PCEC
  - Emphasize good analysis as a critical component of credible cost estimating (model-focused approach vs. data-focused approach)
  - Create an environment that addresses the diverse estimating and analysis requirements across NASA
  - Enable the entire NASA cost community to have ownership and add value to an Agency-wide capability
  - Conduct new normalization and analyses to address the issues identified with NAFCOM
  - Address all elements of the NASA Standard WBS

PCEC Development Philosophy

Tool Development

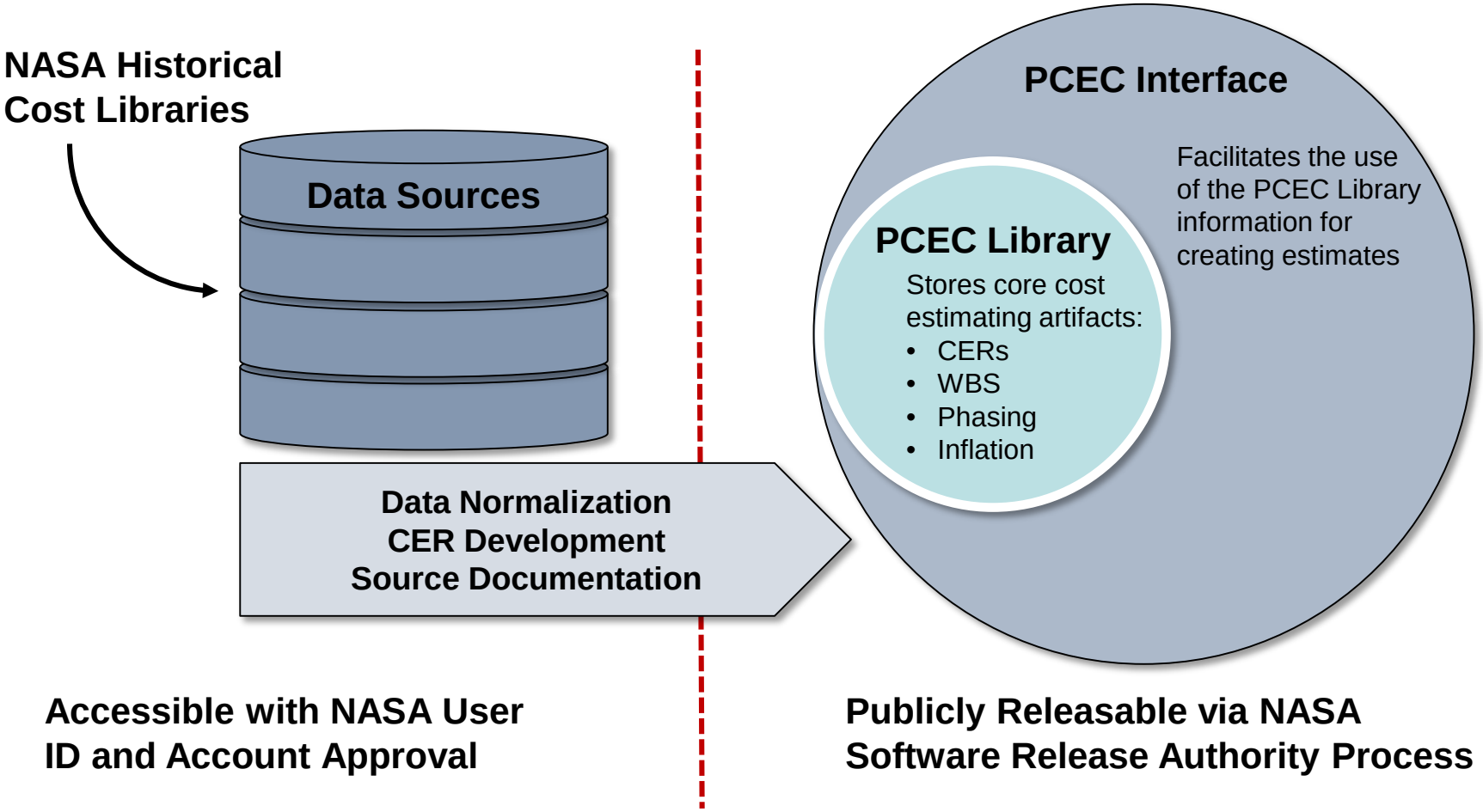
- Simple, Robust, Transparent
- Focus on Flexibility and Capability versus Ease of Use
- Don't Duplicate Existing Capabilities / Models / Tools
- Leverage Existing Software to the Greatest Extent Possible (e.g., Argo, @Risk, Crystal Ball)
- Expect NASA Cost Analysts to Know how to Use Spreadsheets and other Desktop Applications
- Keep the Data behind the NASA Firewall
- Modular, Open Source Architecture

Model Development

- Use the Best Data Possible
- Total Transparency in the Analysis of the Data and the Development of the CERs
- No Cherry Picking the Data Points
- Minimize or Eliminate Subjective Inputs
  - Follow a Data Driven Process for the Derivation of Subjective Inputs
  - Allow the User to Follow the same Process for Determining Input Values
- Emphasize Quality of Input Parameters over Quantity
- Expect the User to Develop the Rationale for the Estimate
  - Model Centric to Data Centric
  - Know the Data

The PCEC Architecture

Key Elements of the PCEC Architecture



PCEC Development Primary Activities

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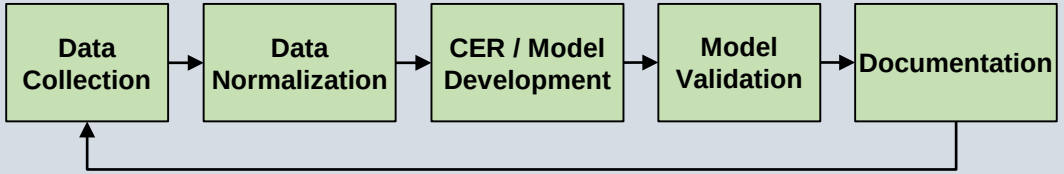
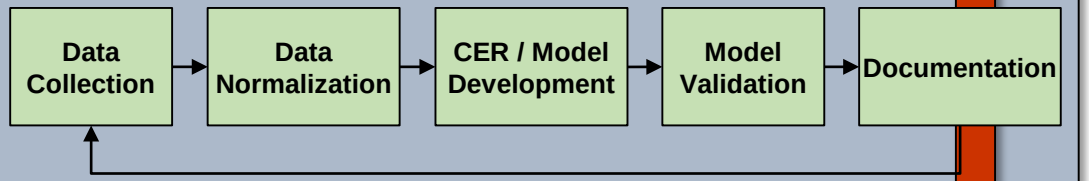
Robotic Spacecraft (Robotic SC)

- New CERs for estimating cost of subsystems for all types of Robotic Spacecraft
- New model for estimating project, payload, and spacecraft support function costs (e.g., PM, I&T)



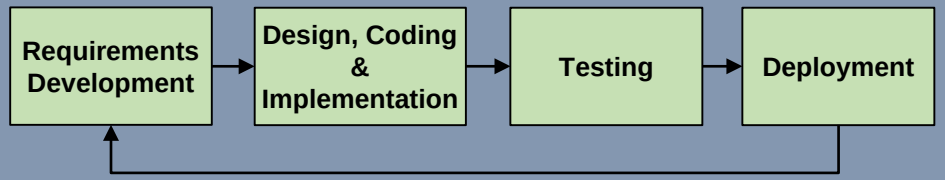
Crewed & Space Transportation Systems (CASTS)

- New CERs for estimating the cost of subsystems on launch vehicles, crewed space structures, and in-space transportation systems
- New cost-to-cost CERs for support functions



PCEC Software Development

- Coding of the Routines to Access cost artifacts used to build a complete space cost estimate
- Development of Estimating Templates for different types of methodologies
- Documentation



Robotic Spacecraft Model

PCEC Robotic SC Model Objective & Approach

Objectives

- Develop a set of cost estimating methodologies tailored for NASA's robotic science missions: Earth Science, Heliophysics, Astrophysics, and Planetary
- Provide full traceability into the data normalization and CER development processes

Approach

Data Collection & Normalization

- Collect cost data from NASA Cost Analysis & Data Requirements (CADRe)
- Identify technical & programmatic input candidates
- Develop repeatable 8-step normalization process

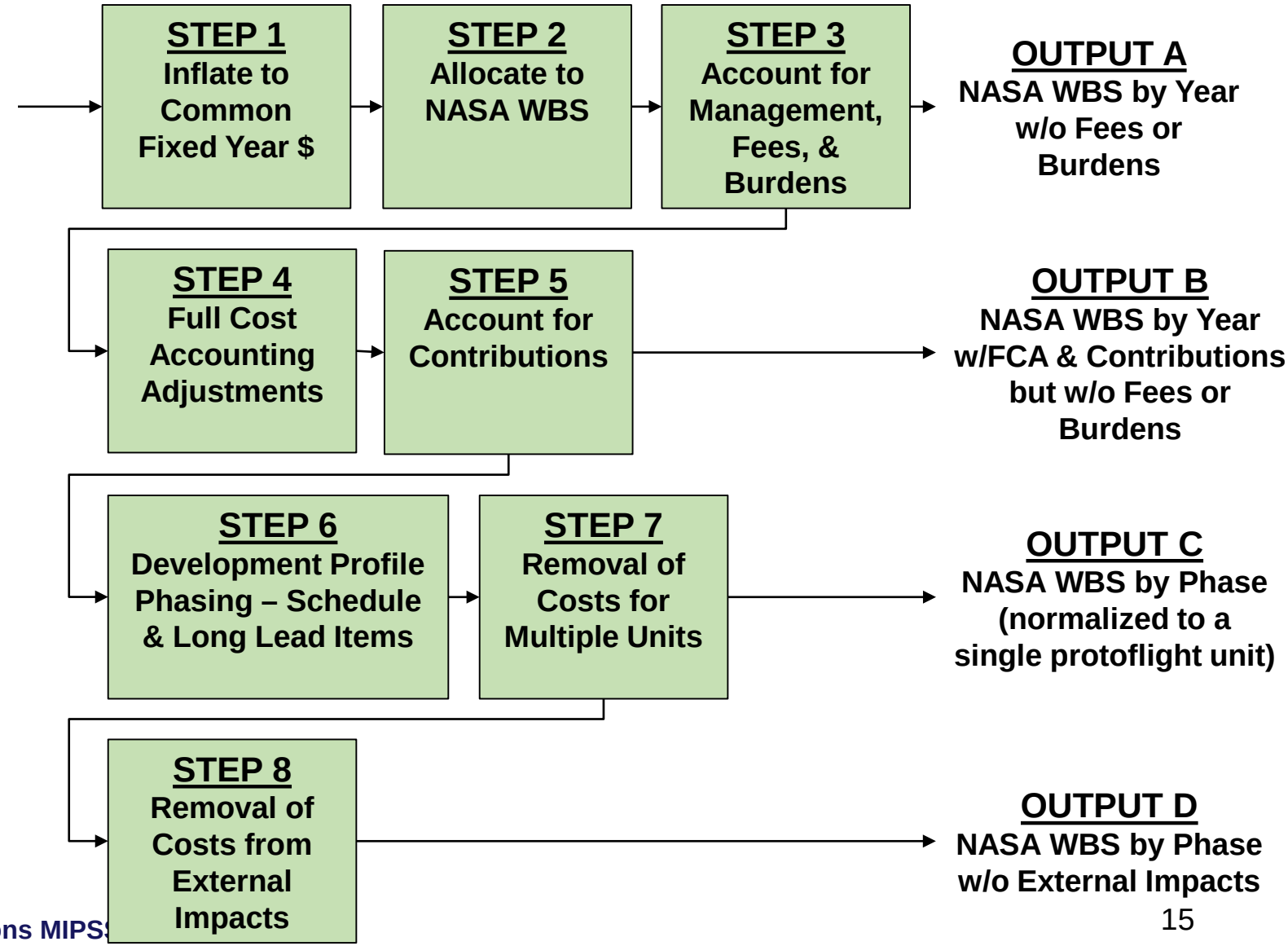
Data Analysis & Model Development

- Explore multiple analysis options to determine most logical modeling approach
- Create, evaluate, and test CERs
  - Spacecraft
  - Support Function
  - Other

Documentation

- Cost Normalization Workbooks
- Cost Assessment Reports (CARs) summarizing data normalization
- CER Input workbooks
- PCEC CER Calculation Workbooks
- CER Validation analysis

PCEC Robotic SC Model Data Normalization Process

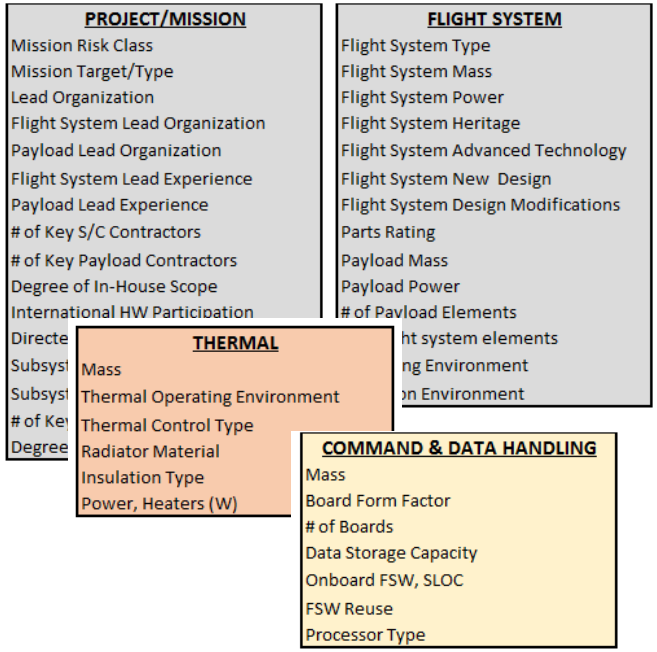


PCEC Robotic SC Model Data Analysis Approach

- Effort began by defining a set of potential model inputs
  - Multiple information sources were reviewed to generate the initial input candidate list, including mass & performance metrics
  - More than 100 input candidates were identified

- Modeling effort explored three alternatives:
  1. Principal Component Analysis (PCA): Narrow the input data set to key parameters before running regression (~10-20 per subsystem)
  2. Regression using Expert Judgment: Use PCA results and expert judgment to narrow the input data set before running regression
  3. Hybrid Approaches: Use regression to develop the initial CERs, with adjustment factors to refine the CERs using additional inputs

Sample Inputs



PCEC Robotic SC Model
Data Analysis Approach (Cont'd)

- PCA was selected as the initial modeling approach to investigate relevant independent variables, followed by iterative multiple regression to develop specific CERs
- For each Subsystem and Support Function, we iterated through the following general process:
  - Segment & transform the normalized data
  - Run PCA to identify variables explaining most of the variation
  - Conduct multiple regression runs to identify potential CERs using from one to five independent variables
  - Evaluate independent variables, statistics, coefficients
  - Select CER for incorporation into the PCEC Library

PCEC Robotic SC Model CER Example

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NOTIONAL

Attitude Control Non-Recurring CER

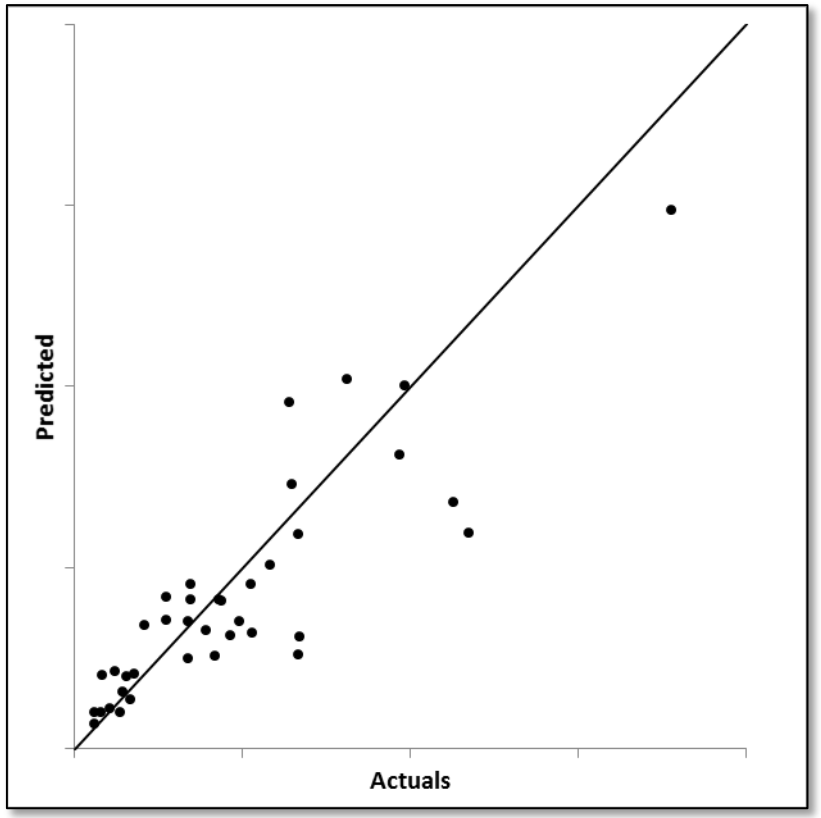
$$Cost = 0.1 * WeightPerUnitKg^{0.42} * OpEnvironment^{0.75} * RadEnvironment^{0.19} * SubsysDesignTime^{0.26} * LaunchYearMinus1960^{1.56}$$

R^2	0.774
Adj R^2	0.740
F-Stat	22.602
F-Stat P-Value	0.000
PING Factor	1.088
SPE	5.49E-02

SSR	22.439
SSE	6.552
SST	28.992
SEE	0.446
Y_Bar	8.151
CV	0.055
Pearson's Cc	0.880

Regression DF	5
Residual DF	33
Total DF	38

Variable Name	Cost	WeightPer UnitKg	OpEnvrmt	RadEnvrmt	SubsysDesi gnTime	LYMinus196 0
Min	574.157	0.610	1.000	1.000	3.467	36.000
Max	17776.345	132.567	5.000	400.000	52.100	54.000
Mean	4779.184	38.961	1.872	30.449	24.979	46.179
Median	4172.519	34.240	2.000	15.000	24.200	47.000
SD	3705.472	29.325	0.978	64.842	11.196	4.833



PCEC Robotic SC Model Summary

- **Methodologies based on newly-normalized data from 42 recently-launched missions, with most data from CADRe**
- **One set of subsystem-level CERs for estimating Non-recurring and Recurring costs (15 CERs)**
  - All are multi-variable power CERs developed using Ordinary Least Squares (OLS) regression of log-transformed data
  - Derived using PCA and multiple regression
  - Assume a protoflight approach for spacecraft development
  - Estimate Gov't + Prime-costs for development and production
- **Another set of CERs for estimating additional costs at the project, payload, and spacecraft levels (6 CERs)**
  - New CERs that estimate the total PM, SE, MA, and I&T costs; allocations distribute costs to the project, payload, and spacecraft level
  - New CERs to estimate the Mission Operations Systems / Ground Data Systems (MOS/GDS) development costs
  - Developed using a PCA approach

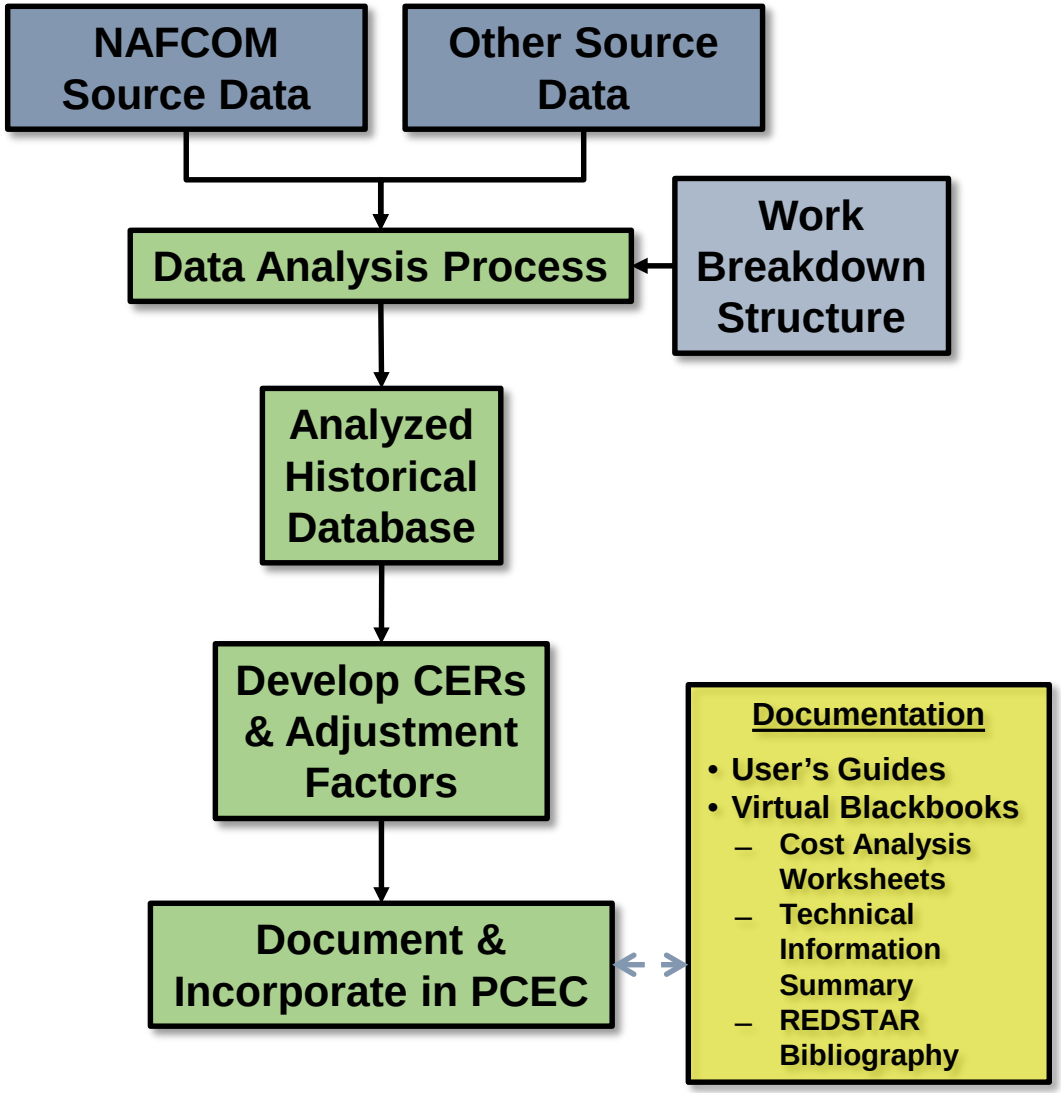
Crewed and Space Transportation Systems (CASTS) Model

PCEC CASTS Model Objectives

Objectives

- Develop a new, unique cost model for use in estimating space transportation systems, including crewed systems, earth-to-orbit systems, and in-space transportation systems
- Construct model from a historical database consisting exclusively of transportation/crew systems
- Empower users to create *Credible, Supportable, Defendable* estimates

PCEC CASTS Model Approach



1. Develop Overall WBS
2. Identify Source Data
   - NAFCOM-heritage systems: Trace back to original sources; re-evaluate using common definitions/assumptions; fit to CASTS WBS
   - New systems: Understand/analyze source data; evaluate using common definitions/assumptions; fit to CASTS WBS
3. Normalize Source Data
   - Convert to common year & units
   - Separate out elements of cost: Design & Development, First Unit, System Test Hardware, etc.
4. Assign to Appropriate CASTS WBS Elements
5. Develop CASTS CERs
   - Identify potential independent variables
   - Develop CER equations
   - Evaluate CER "goodness"
6. Document Analysis

PCEC CASTS Model
Data Normalization & Analysis

- Model Development Approach
  - Perform iterative multiple regression with a small set of potential independent variables; mass as primary input with additional variables unique to subsystems
  - Create & evaluate CERs in both power and linear forms based on data
- Why this approach? Significant data "clutter"
  - Minimal number data points with multiple potential independent variables (overfitting, potential multi-collinearity)
  - Lack of/dissimilar definitions of technical variables between sources
  - Poor predictive value (P-values >> .05)
  - Counter-intuitive results (cost ↑ over time, cost ↓ increased complexity)
  - Conflicting/countervailing influences between potential variables
- Calculated "adjustment factor" for each data point
  - Ratio of the actual to predicted value for a data point
  - Not a "complexity" factor – says nothing about why value is what it is

PCEC CASTS Model Example CER

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NOTIONAL

Adapters Design & Development CER

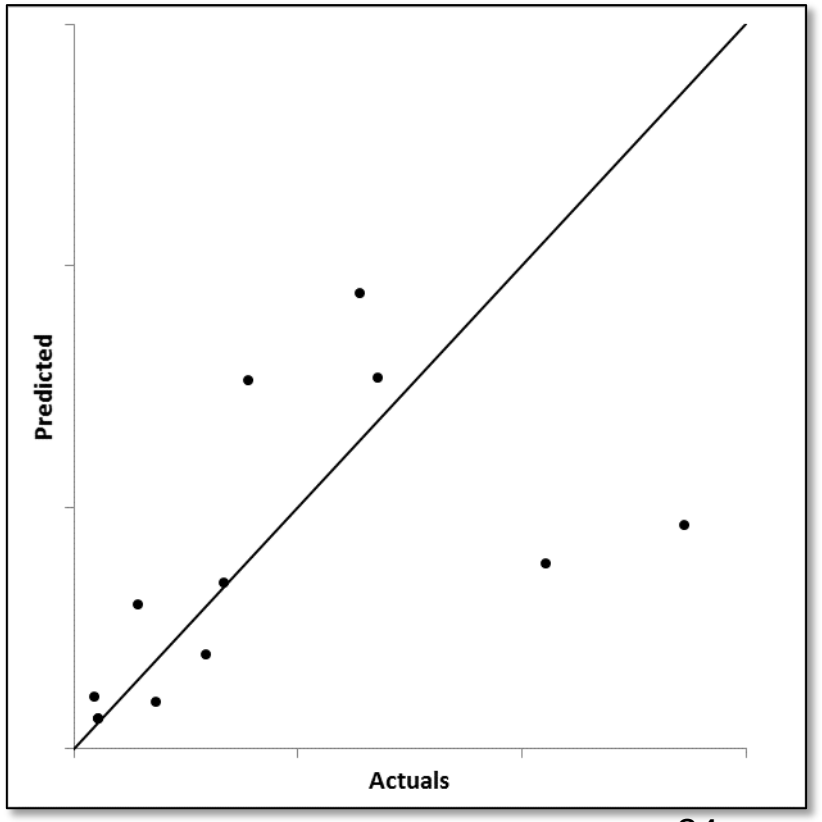
$$Cost = 0.45 * WeightPerUnit^{0.83}$$

R^2	0.691
Adj R^2	0.661
F-Stat	22.412
F-Stat P-Value	0.001
PING Factor	1.213
SPE	0.28647763

SSR	10.405
SSE	4.643
SST	15.047
SEE	0.681
Y_Bar	2.554
CV	0.267
Pearson's Cc	0.832

Regression DF	1
Residual DF	10
Total DF	11

Variable Name	Cost	WeightPer Unit
Min	2.337	120.000
Max	68.068	5262.000
Mean	21.772	1691.250
Median	15.667	1179.000
SD	21.122	1754.561



PCEC CASTS Model Summary

- **Methodologies based on data from ~34 historical launch vehicle stages, crewed vehicles, and related space transportation systems/subsystems**
- **One set of CERs for estimating subsystem-level costs of Design and Development (D&D) and Flight Unit (43 CERs)**
  - Nearly all are single-variable power CERs (with weight as the independent variable); a small number are linear CERs or multi-variable power CERs
  - Adjustment factors provide an analogous estimating supplement
  - Estimate Prime costs
- **Another set of CERs for estimating supporting costs (e.g., PM, ground support equipment, tooling) at the spacecraft level (8 CERs)**
  - Most are cost-to-cost CERs (use flight system cost as base)
  - Estimate Prime-level costs only; factors used for Program/Project level

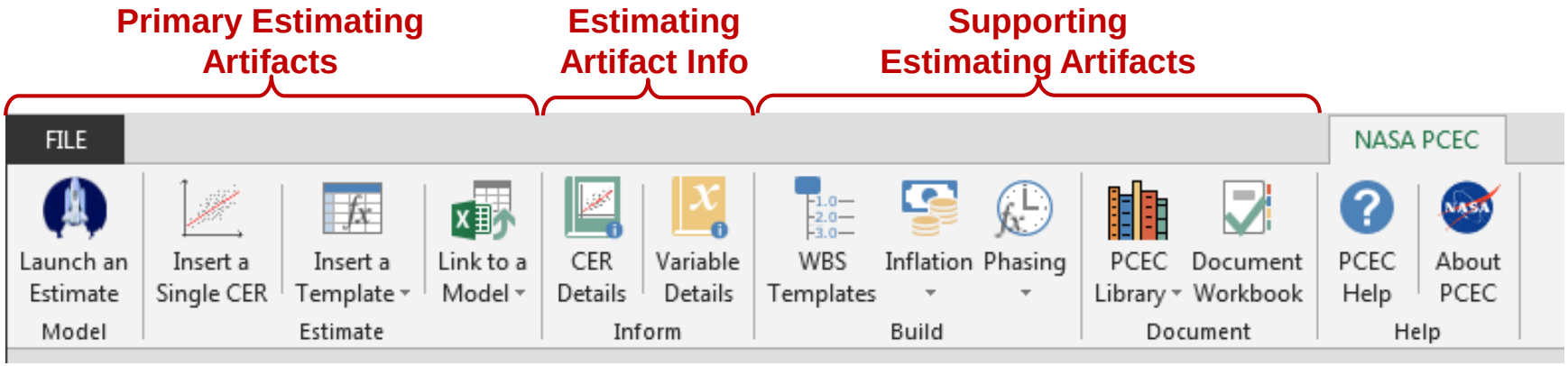
PCEC Capability Overview

PCEC Interface Overview

The PCEC Interface…

- is an Excel Add-in that appears as its own tab in the Excel Ribbon, with buttons to access capabilities for building an estimate in Excel
- contains a compressed copy of the PCEC Library and associated artifacts needed to build an estimate, including…
  - CERs
  - Statistics about the CERs
  - Other worksheets with WBSs, Inflation, specialized methodologies, etc.
- is compatible with Windows versions of MS Office
  - Excel 2007, 2010, and 2013; Excel 2016 TBD
  - Mac users must use a virtualization program to run Windows
- is completely open: no code passwords, protected sheets, etc.

PCEC v2.1 Interface Ribbon Overview



The primary section contains the key elements used to create a cost estimate in an Excel workbook

- The "Launch" feature, which auto-generates a complete estimate from a user-customized WBS
- Ability to insert single CERs into a worksheet
- Ability to insert pre-formatted templates into a workbook that estimate the DDT&E and production costs of a subsystem
- Linking to other NASA-related cost models (e.g., NICM)

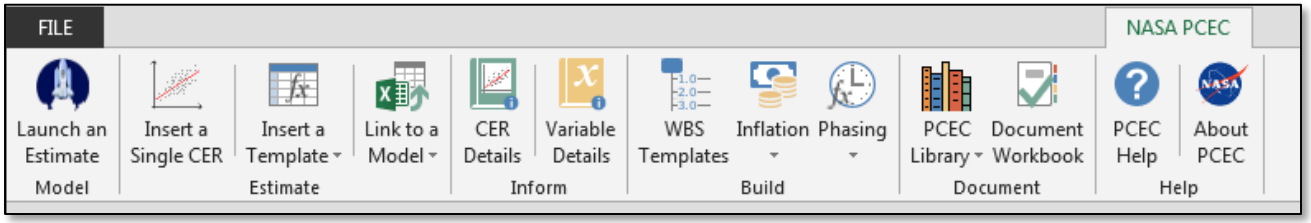
The middle section provides access for learning more about the specific estimating artifacts that are available to users

- Information about the CERs: regression statistics, descriptive statistics, missions used
- Definitions and variables, their input units, and lists of valid inputs

The final section contains supporting elements for adding elements to complete an estimate

- Starting NASA Standard WBSs
- Inflation worksheets for escalating
- Phasing options for developing a by-year profile for the cost estimate
- Auto-generation of a documentation workbook for all CERs used in an estimate
- Help documents

PCEC v2.1 Components



Robotic Science Missions

- Spacecraft Subsystem CERs
- Support Function CERs
- NASA Instrument Cost Model
- MOS/GDS Development CERs
- Science Team Wrap Factors
- Launch Services ROM Estimator
- PCEC v1 Legacy CERs
- First Pound Cost CERs

Launch Vehicles/Human Spaceflight Missions

- Crewed and Space Transportation Systems (CASTS) Subsystem CERs
- Cost-to-cost Support Function CERs
- PCEC v1 Legacy CERs
- First Pound Cost CERs
- Wrap Factors

Estimating Support

- Thruput Templates
- CER Library
- WBS Templates
- Help File
- Inflation Indices
- Cost Phasing

Outside of PCEC

- Robotic Spacecraft data analysis spreadsheets and cost analysis reports
- CASTS “Virtual Blackbooks”
- CASTS User’s Guide
- Cost Analysis Data Requirements (CADRe) documents & backup data
- Other historical cost and technical data in the REDSTAR Library

PCEC v2.1 Model Capabilities

- PCEC v2 is currently best suited for estimating the cost to design, develop, and produce the following types of space systems
  - Spacecraft: Earth Orbiting Satellites, Planetary Probes, Rovers
  - Launch Vehicles: Multi-stage rockets, liquid and solid engines
  - Human Space Flight Systems: Crew Capsules, Orbiters, Habitats
- PCEC v2 CERs are designed to estimate at the subsystem level
  - Historical v1 Legacy CERs can estimate at the lower level but are separate from the Robotic SC and CASTS Models
- PCEC v2 currently does not have the capability to estimate…
  - Cubesats, Balloons, Aircraft
  - Nanosat Launchers, Sounding Rockets
  - Human hardware elements (e.g., space suits)

PCEC Today

- PCEC v2.1 is the latest version available (released in Aug 2016), which includes enhancements for estimating more elements across the NASA Standard WBS
- The general public can obtain PCEC (with some export restrictions) via the NASA Software Repository

PCEC Email Contact: MSFC-PCEC@mail.nasa.gov
Application Website: https://software.nasa.gov/ , search for PCEC

- Ongoing data analyses and code development will continue to evolve the tool for future releases

PCEC Summary

- PCEC replaces NAFCOM as NASA's in-house developed parametric cost estimating tool, accessible by many organizations
- PCEC is not just a software tool but also a set of underlying analytical efforts to provide quality models within the tool
  - New normalizations and CERs for Robotic SC and CASTS that follow a traceable, consistent approach
  - Transparent calculations within the tool
  - Tailorable environment to meet an individual or organization's unique estimating needs

- Questions?

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Backup

PCEC Robotic SC Model Mission Database

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	MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program
1	TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm
2	MAVEN	11/18/13	GSFC	LMA	Planetary
3	LADEE	9/6/13	GSFC	ARC	Planetary
4	IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX
5	Van Allen Probes	8/30/12	GSFC	APL	Heliophysics/LWS
6	NuSTAR	6/13/12	JPL	OSC	Astrophysics/Explorer
7	MSL	11/26/11	JPL	JPL/LMA	Planetary/Mars Expl
8	GRAIL	9/10/11	JPL	LMA	Planetary/Discovery
9	Juno	8/5/11	JPL	LMA	Planetary/New Frontiers
10	Glory	3/4/11	GSFC	OSC/Swales	Earth Sciences
11	GOES (-P)	3/4/10	GSFC/NOAA	Boeing/SGT	Earth Sciences
12	SDO	2/11/10	GSFC	GSFC	Heliophysics
13	WISE	12/14/09	JPL	BATC	Astrophysics/Explorer
14	LCROSS	6/18/09	ARC	NG	Planetary/Discovery
15	LRO	6/18/09	GSFC	GSFC	Planetary
16	KEPLER	3/6/09	JPL	BATC	Astrophysics/Discovery
17	OCO	2/24/09	JPL	OSC	Earth Science
18	IBEX	10/19/08	SwRI	OSC	Astrophysics/Explorer
19	DAWN	9/27/07	JPL	OSC/JPL	Planetary/Discovery
20	Phoenix	8/4/07	JPL	LMA	Planetary
21	AIM	4/25/07	LASP	OSC	Heliophysics
22	THEMIS	2/17/07	UCB	Swales	Astrophysics/Explorer
23	STEREO	10/26/06	GSFC	APL	Heliophysics
24	CLOUDSAT	4/28/06	GSFC	BATC	Earth Sciences
25	NEW HORIZONS	1/19/06	APL	APL	Planetary/New Frontiers
26	MRO	8/12/05	JPL	LMA	Planetary/Mars Expl
27	DEEP IMPACT	1/12/05	JPL	BATC	Planetary/Discovery
28	Swift	11/20/04	GSFC	Spectrum Astro	Astrophysics/Explorer
29	MESSENGER	8/3/04	APL	APL	Planetary/Discovery
30	Spitzer	8/25/03	JPL	LMA	Astrophysics
31	MER	6/10/03	JPL	JPL	Planetary/Mars Expl
32	GALEX	4/28/03	JPL	OSC	Astrophysics/Explorer
33	RHESSI	2/5/02	UCB	Spectrum Astro	Heliophysics
34	TIMED	12/7/01	APL	APL	Earth Sciences
35	GENESIS	8/8/01	JPL	LMA	Planetary/Discovery
36	Mars Odyssey	7/7/01	JPL	LMA	Planetary/Mars Expl
37	WMAP	6/30/01	GSFC	GSFC	Astrophysics/Explorer
38	WIRE	3/5/99	GSFC	GSFC	Astrophysics/Explorer
39	TRACE	4/2/98	GSFC	GSFC	Astrophysics/Explorer
40	Cassini	10/15/97	JPL	JPL	Planetary/Outer Planets
41	Mars Global Surveyor	11/7/96	JPL	LMA	Planetary/Mars Expl
42	NEAR	2/17/96	APL	APL	Planetary/Discovery
		Group 1	Group 2	Group 3	

PCEC CASTS Model Mission Database

Engineering Cost Office

Roster of systems currently included in CASTS CER datasets

Launch Vehicles
Atlas V Common Core Booster
Atlas V Centaur
Apollo Command/Service Module
Apollo Lunar Module
Centaur D
Centaur G' (Shuttle Centaur)
Centaur G' CISS - ASE
Shuttle External Tank
Shuttle Orbiter
Shuttle Solid Rocket Motor
Shuttle Solid Rocket Booster
Saturn V 1st Stage (SIC)
Saturn V 2nd Stage (SII)
Saturn V 3rd Stage (SIVB)
Titan Centaur
Titan IV 5m Fairing
Atlas I, II, IIA, IIAS
Super Lightweight External Tank

Liquid Engines
F1
J2
J2X
RS27
RD180
RL10
RS68
SSME

Solids
Titan IV SRMU
Athena Castor 120
Trident D5
Shuttle RSRM
Atlas IIAS Castor 4A
Atlas V SRM
Ariane V EAP-P230
Pegasus

Software
SSME Adv Health Mgt Sys
Orbiter Cockpit Avionics Upgrade
Orbiter Primary Avionics Software Sys
Orbiter Backup Flight Software
BRAHMS
DART
X33
Centaur G'
Atlas II
Atlas V