National Aeronautics and Space Administration

Project Cost Estimating Capability (PCEC) Updates for 2022

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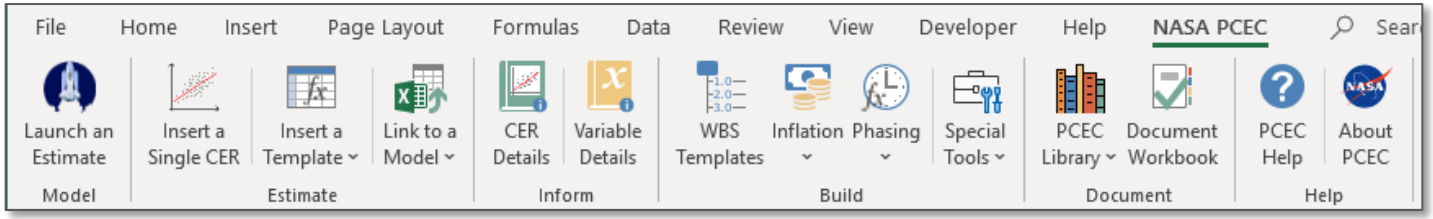
NASA Cost & Schedule Symposium

April 27, 2022

- PCEC Overview
- Robotic Spacecraft Updates
  - Normalizing for COVID
  - Outlier estimating
  - Integration & Test CERs
- Other PCEC Work in Progress

Overview

NASA Project Cost Estimating Capability (PCEC)

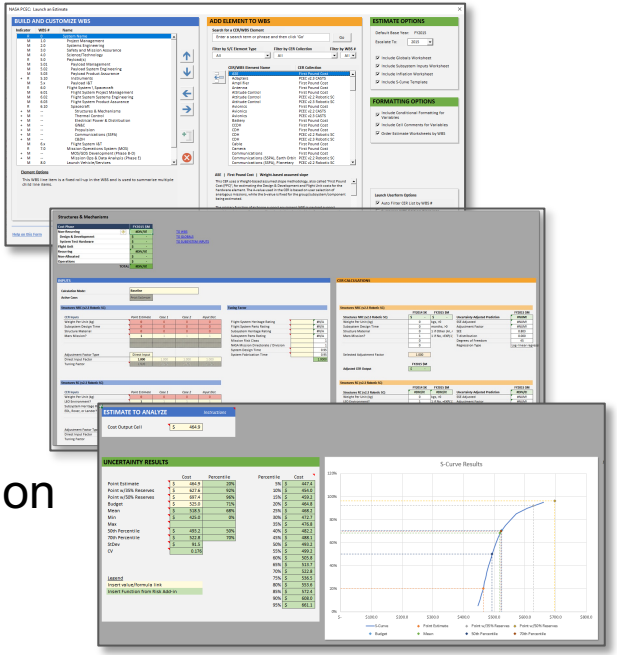


PCEC is the primary NASA in-house developed parametric tool for estimating the cost of robotic missions, launch vehicles, crewed vehicles, etc.

- Overarching tool for creating an estimate that spans the full NASA WBS
- CERs included for estimating the costs of a flight system and project support functions
- Connects to other NASA-sponsored specialized tools to cover the complete NASA WBS (e.g., NICM, MOCET)
- Excel-based (add-in in the Ribbon) with completely visible calculations and code
- Consists of the PCEC Interface (the Ribbon and supporting code) and the PCEC Library (artifacts used to estimate cost)
- Available to the General Public

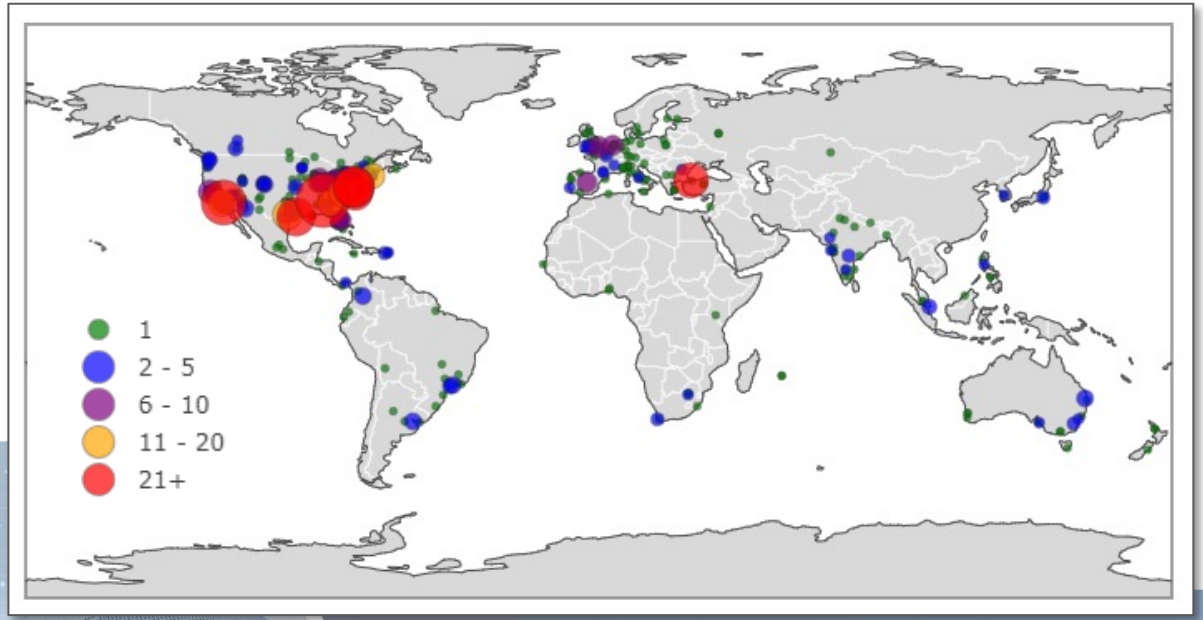
What is PCEC?

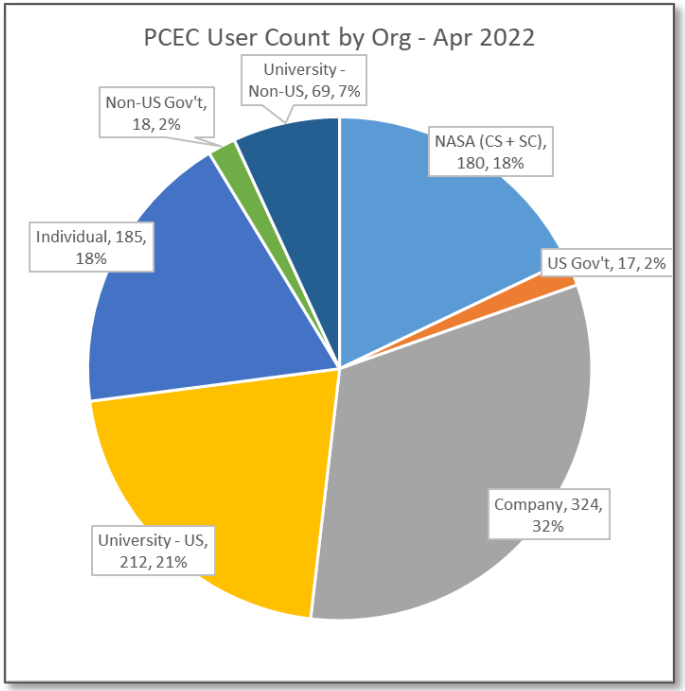
- PCEC v2.3 was released April 2021
  - Expanded the dataset of science missions (now 49)
  - Significant update of the Robotic Spacecraft CERs
  - Minor updates to the Crewed and Space Transportation Systems (CASTS) CERs
  - Overhaul of the estimating worksheets and templates
  - Linkages to the latest external models
- Available on ONCE and the NASA Software Catalog
- Feedback on v2.3 has been limited but primarily focused on estimating changes introduced for Robotic Spacecraft



PCEC Today

- Latest User Statistics:
  - 1005+ users/downloaders from 51 countries
  - Primary growth over the past year has been from academic users and unaffiliated individuals





PCEC User Counts – April 2022

- Mission Set & New Candidates
- Normalizing COVID Impacts
- Improving Performance (Flagship/I&T)
- Potential Alternative CER Development
- Future Plans

Robotic Spacecraft Topics

PCEC v2.3 Mission Set + Additional Candidates

- PCEC v2.3 CERs based on 49 Missions
- Data from 6 new missions has been collected/normalized
  - Includes SMAP, JPSS-1, PSP, Mars 2020, TESS, and IXPE
- 9 additional launched missions
  - Some missions with completed launch CADRe's are missing subsystem cost breakouts (ICON, ICESat-2, TROPICS)
  - CADRe data for other 6 expected soon
- 3 missions launching soon
  - Psyche, NEA Scout, and PACE

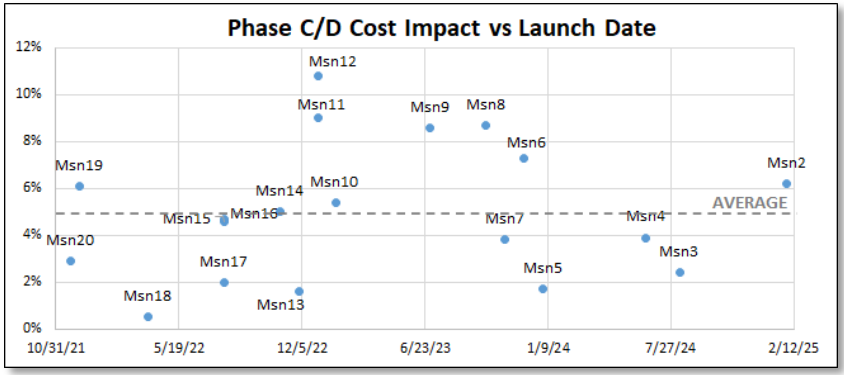
	MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program
	Missions for PCEC v2.3				
1	TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm
2	MAVEN	11/18/13	GSFC	LMA	Planetary
3	LADEE	9/6/13	GSFC	ARC	Planetary
4	IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX
5	Van Allen Probes	8/30/12	GSFC	APL	Heliophysics/LWS
6	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
43	GPM	2/27/14	GSFC	BATC	Earth Sciences
44	OCO-2	7/2/14	JPL	OSC	Earth Sciences
45	MMS	3/12/15	GSFC	GSFC	Astrophysics/Explorer
46	OSIRIS-REx	9/8/16	GSFC	LMA	Planetary/New Frontiers
47	GOES-R	11/19/16	GSFC/NOAA	Boeing/SGT	Earth Sciences
48	CYGNSS	12/15/16	SwRI	SwRI	Earth Sciences
49	InSight	5/5/18	JPL	LMA	Planetary/Discovery

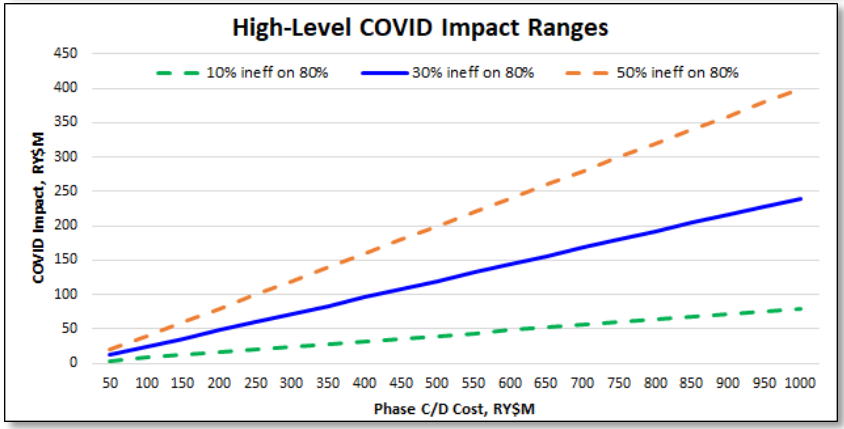
	MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program
	New Mission CAR Candidates				
n1	SMAP	1/31/15	JPL	JPL	Earth Sciences
n2	JPSS-1	11/10/17	GSFC	BATC	Earth Sciences
n3	Solar Probe	8/6/18	GSFC	APL	Heliophysics
n4	Mars 2020	7/30/20	JPL	JPL	Planetary
n5	TESS	3/20/18	GSFC	OSC	Astrophysics/Explorer
n6	IXPE	12/9/21	MSFC	Ball	Astrophysics/Explorer
n7	ICESat-2	9/15/18	GSFC	OSC	Earth Sciences
n8	ICON	10/26/18	UCB	OSC	Astrophysics/Explorer
n9	TROPICS	6/30/21	MIT	BCT	Earth Sciences
n10	TDRSS-M	8/18/17	GSFC	Boeing	Space Comm
n11	Landsat-9	9/27/21	GSFC	NG	Earth Sciences
n12	Lucy	10/16/21	GSFC	LMSS	Planetary
n13	DART	11/23/21	APL	APL	Planetary
n14	JWST	12/25/21	GSFC	NG	Astrophysics
n15	GOES-T	3/1/22	GSFC	LMSS	Earth Sciences
n16	Psyche	8/1/22	JPL	SSL	Planetary
n17	NEA Scout	2022	MSFC	JPL	Planetary
n18	PACE	2023	GSFC	GSFC	Earth Sciences

Key:
- Heliophysics
- Astrophysics
- Earth Sciences
- Planetary

PCEC Robotic Mission Database could grow from 49 to 64-67 data points *(depending on availability of data details)*

- Level of impact can vary depending on where each project was in its development cycle, use of contractors/subcontractors, international contributions, launch date flexibility, and many organization-specific constraints
- Although data from 25 projects shows significant variability, the impact appears to be greatest for missions scheduled to launch in 2023
- 30% inefficiency for 80% of the cost elements appears to be a reasonable high-level approximation of cost impacts due to COVID
  - An inefficiency range from 10-50% on 80% of all costs captures impacts for most projects



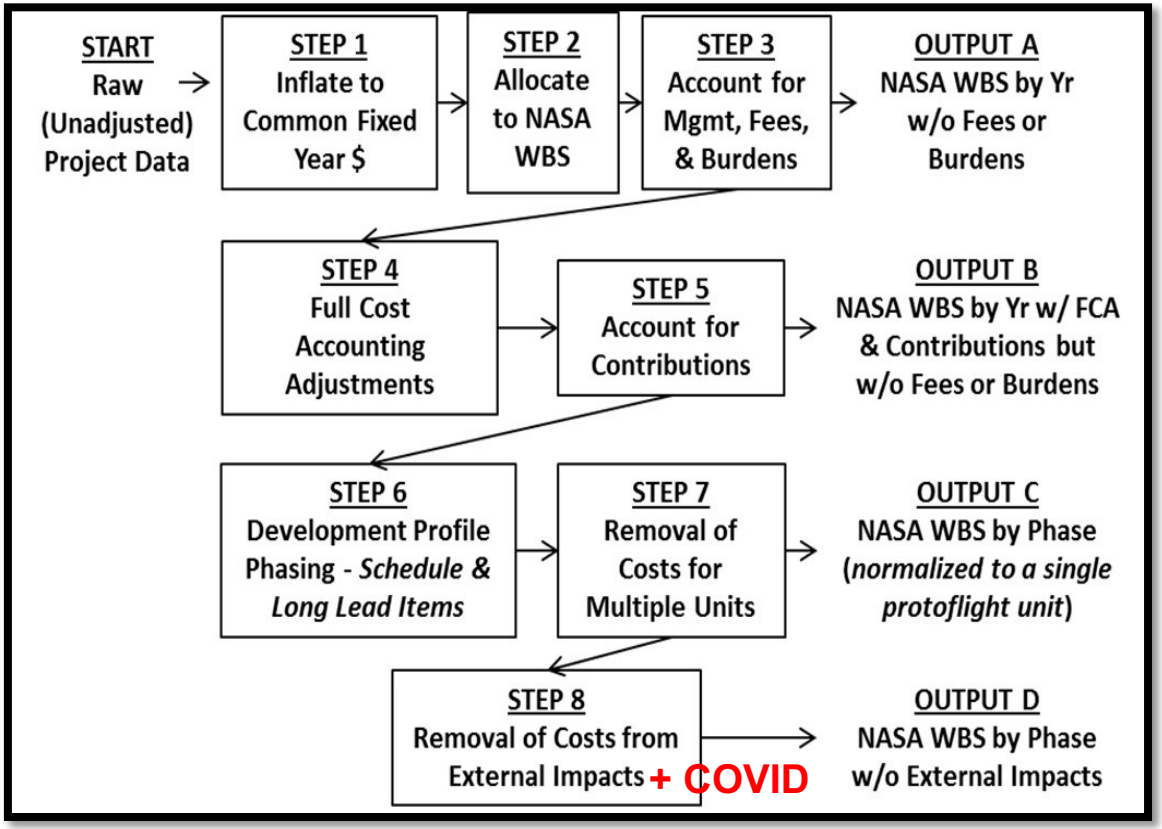


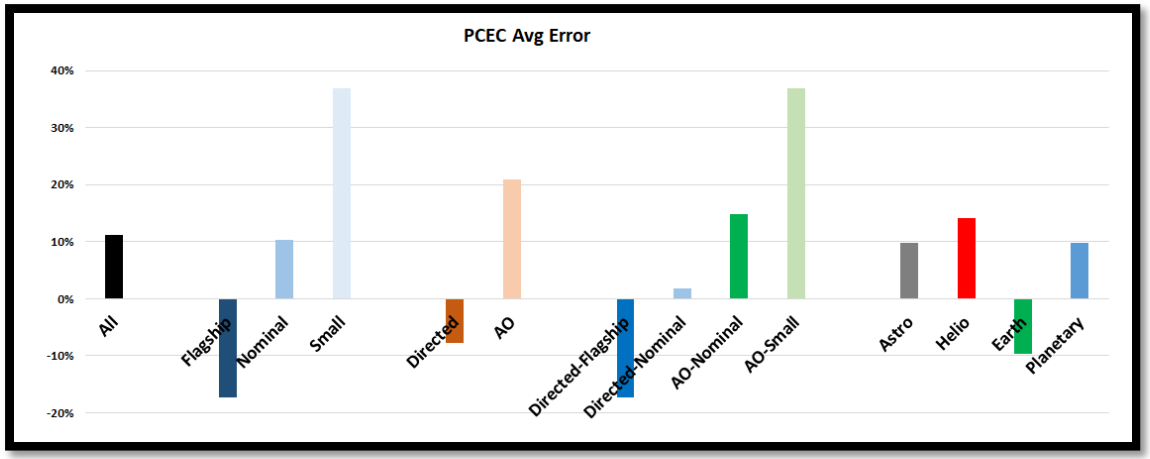
COVID impacts can be captured by the External Factors PCEC normalization step

How to Normalize COVID Impacts?

Where are COVID impacts captured in the normalization process?

- COVID impacts will be normalized out of any new missions added to the PCEC data set.
- Removal of the impacts will be reflected in Step 8 of the normalization process which includes other external impacts such as labor strikes, hurricane impacts, etc.

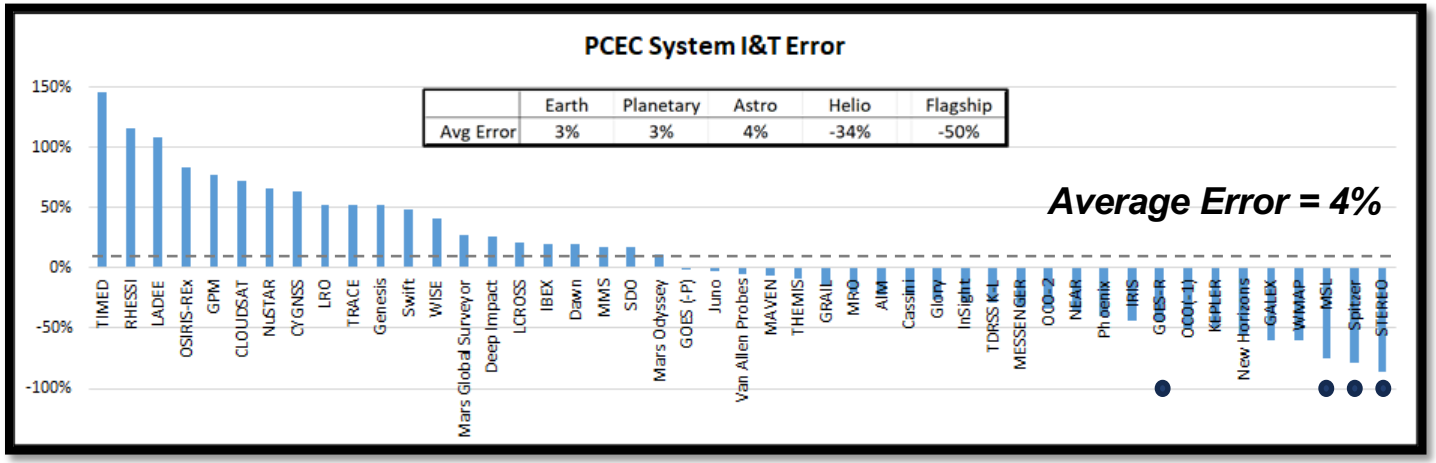


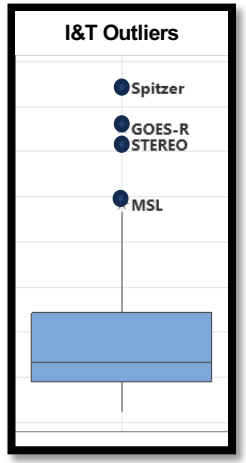


Data includes 52 projects (vs. 49 used for PCEC v2.3)

- PCEC feedback has identified lower-than-expected estimates for Flagship missions
- Flagship mission data also appears to be affecting estimates for Smaller missions
- Multiple options for improving PCEC performance for Flagship missions are being explored
  - New CERs or Tuning adjustments for current CERs
- Efforts to develop Tuning adjustments have not been successful – new input candidates to support New CERs are being identified

Improving Performance for Flagship Missions





- Although the PCEC average error System I&T is only 4%, the error is much greater for Flagship and Heliophysics missions and shows significant variability for specific projects
- Recent experience and user feedback has identified higher-than-expected I&T estimates for recent small and medium sized flight systems
- Significant effort has not identified a better approach for this CER yet
  - Current input candidates do not seem to be adequate & additional options are being explored

Improving Performance for System I&T Estimates (WBS 10.0)

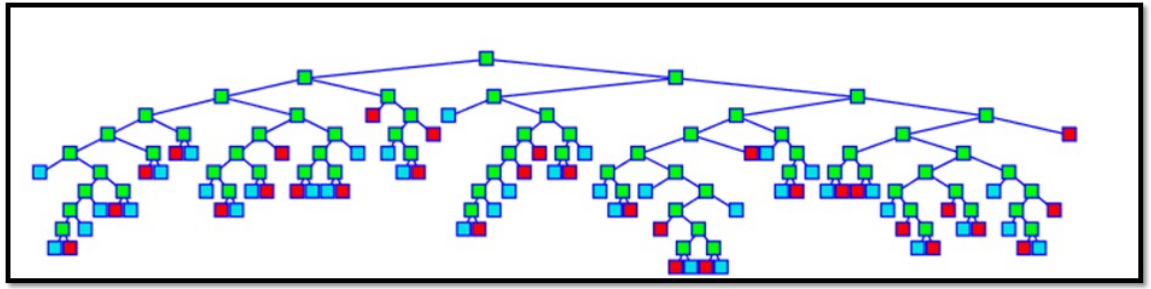
- Given difficulties identifying trends to improve estimates for Flagship Missions and System I&T, additional input candidates have been explored
- *Observation*: PCEC inputs characterizing the payload are limited
  - Payload Mass & Power are input candidates for System I&T, but mass and power do not seem to accurately affect payload complexities that affect System I&T
- Other options to characterize the payload complexity with respect to accommodations are being explored
  - Metrics used for a past study to represent Payload "Level of Difficulty" are shown here
  - These metrics are under consideration for development of "Figure of Merit" input candidates to represent payload complexity
  - A Payload Accommodations Database is under development to collect technical metrics related to Mass, Power, Thermal, Size/Volume, Data Rates, and Pointing Reqs

Parameter	High (9-7)	Medium (6-4)	Low (3-1)
Mass	> 200 kg	< 140 kg	< 60 kg
Power	> 200 W	< 140 W	< 60 W
Data Rate	Gbs	Mbs	Kbs
Optics/antenna size	> 80 cm	< 50 cm	< 30 cm
Spectral resolution	hyperspectral	narrow	broadband
Cooling	< 40 K	> 70 K	passive
Detector arrays	2D	1D	single detectors
Mechanisms	> 2	2	none
In situ	sample return	mass spectrometer	electric/magnetic fields
Complex operations	> 2 spacecraft	2 spacecraft	1 spacecraft
Contamination	EUV	UV	VIS/IR
Pointing	arcsec	arcmin	none, e.g. spinning
Radiation exposure / environment	extreme temperature and/or radiation	high temperature and/or radiation	none/SAA
Heritage	none	some	significant

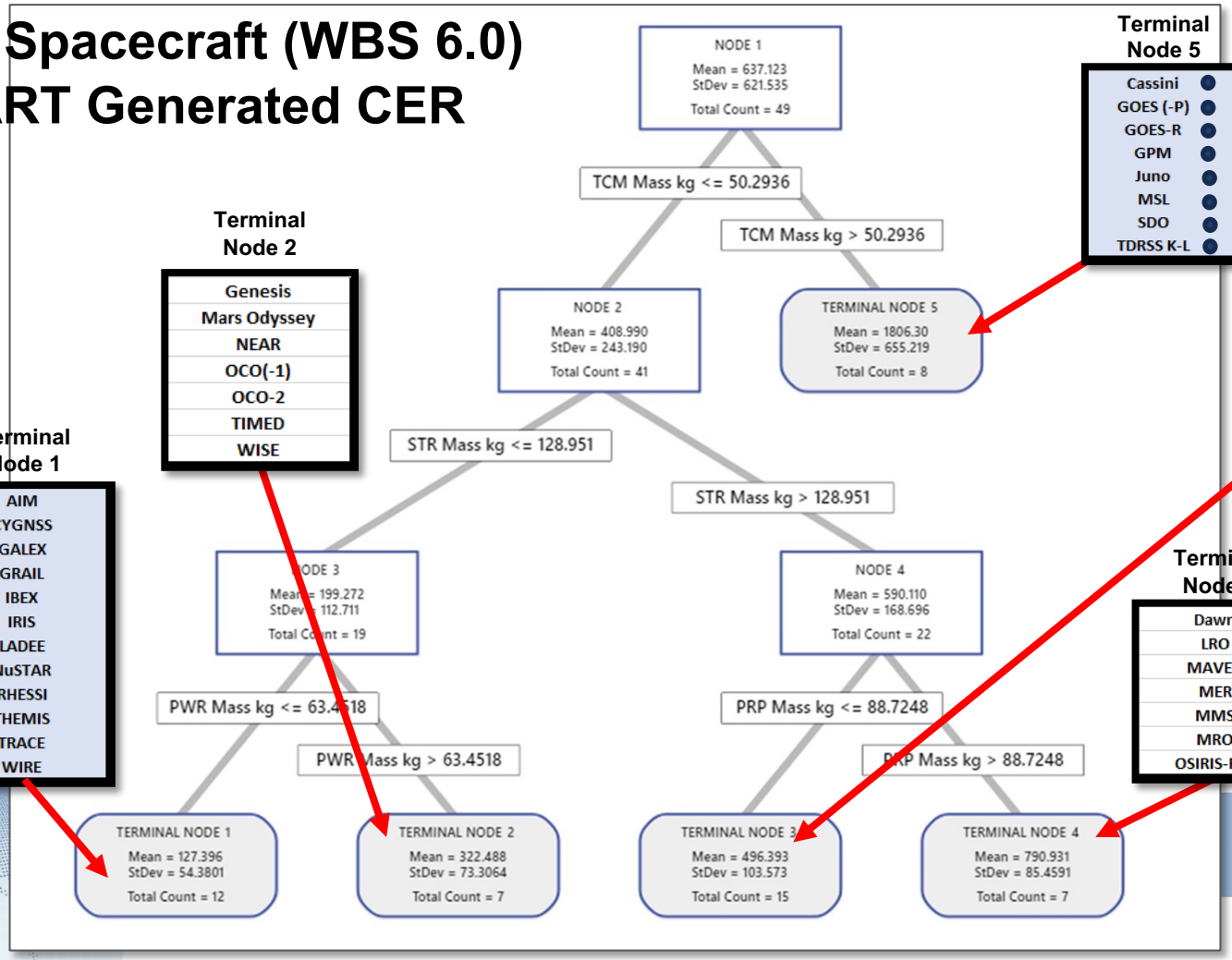
Understanding the Role of Payload Accommodations

Tree Based Learning Algorithms

- Classification and Regression Tree (CART) analysis is a tree based method which uses a recursive partitioning method to build regression trees for predicting continuous dependent variables.
- In CART, each non-terminal node (green square) identifies a split condition or branch, to yield optimum prediction in the response variable. Each terminal node or leaf (blue/red squares) provides a mean estimate based on prior decisions.
- CART provides predictive models with high accuracy, stability and ease of interpretation. Unlike linear models, they map non-linear relationships quite well and do not require database pre-processing for missing values, removal of outliers or log transformation of the data set.
- Early implementation of the CART methodology appears to provide an alternate path to developing supplemental PCEC CERs.



Total Spacecraft (WBS 6.0) CART Generated CER

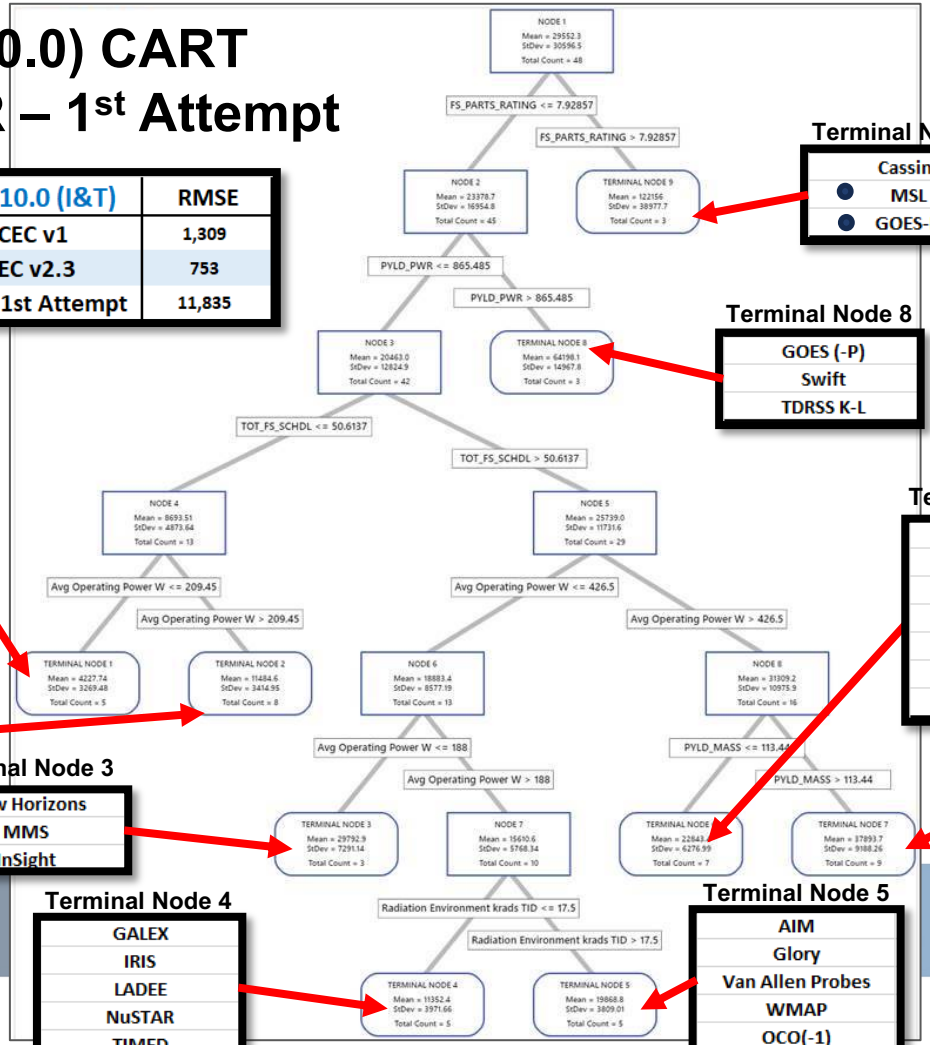


- Indicates a significant PCEC v2.3 Outlier

I&T (WBS 10.0) CART Generated CER – 1st Attempt

WBS 10.0 (I&T)	RMSE
PCEC v1	1,309
PCEC v2.3	753
CART - 1st Attempt	11,835

- Indicates a significant PCEC v2.3 Outlier



Terminal Node 9
- Cassini
- MSL
- GOES-R

Terminal Node 8
- GOES (-P)
- Swift
- TDRSS K-L

Terminal Node 1
- IBEX
- MER
- THEMIS
- TRACE
- CYGNSS

Terminal Node 6
- Dawn
- Deep Impact
- LRO
- MAVEN
- MESSENGER
- Phoenix
- OSIRIS-REx

Terminal Node 7
- CLOUDSAT
- Juno
- KEPLER
- MRO
- SDO
- Spitzer
- STEREO
- GPM
- OCO-2

Terminal Node 2
- Genesis
- GRAIL
- LCROSS
- Mars Global Surveyor
- NEAR
- Mars Odyssey
- RHESSI
- WISE

Terminal Node 3
- New Horizons
- MMS
- InSight

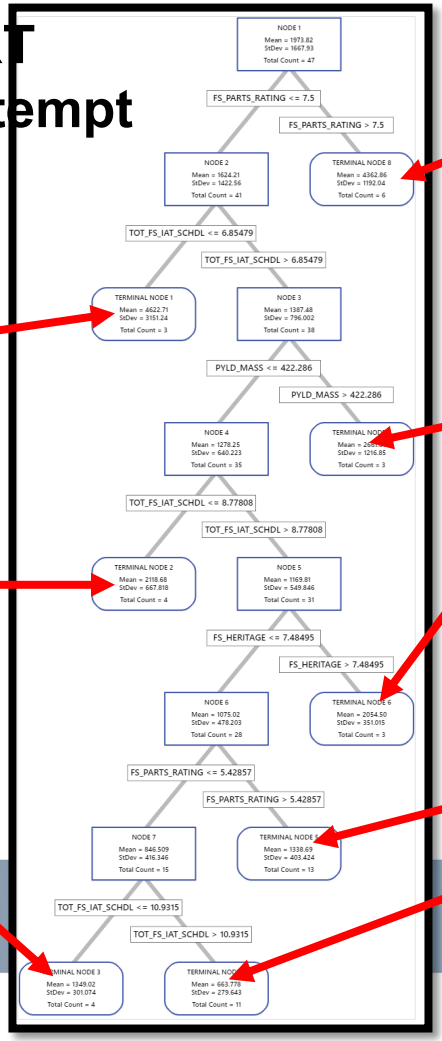
Terminal Node 4
- GALEX
- IRIS
- LADEE
- NuSTAR
- TIMED

Terminal Node 5
- AIM
- Glory
- Van Allen Probes
- WMAP
- OCO(-1)

I&T (WBS 10.0) CART Generated CER – 2nd Attempt

- Indicates a significant PCEC v2.3 Outlier

WBS 10.0 (I&T)	RMSE
PCEC v1	1,309
PCEC v2.3	753
CART - 1st Attempt	11,835
CART - 2nd Attempt	1,013



Term Node 1
- Spitzer*
- STEREO*
- TRACE

Term Node 2
- GALEX
- NEAR
- WMAP
- OCO(-1)

Term Node 3
- AIM
- IRIS
- LCROSS
- WISE

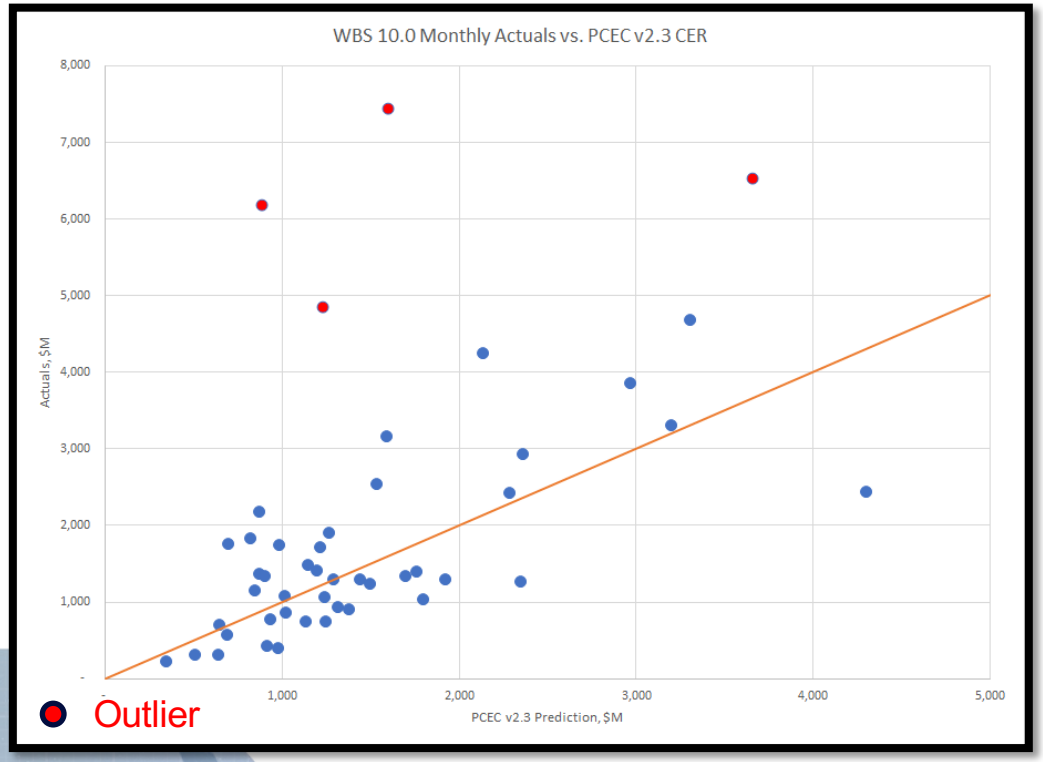
Term Node 4
- Glory
- IBEX
- LADEE
- LRO
- NuSTAR
- RHESSI
- THEMIS
- TIMED
- Van Allen Probes
- MMS
- CYGNSS

Term Node 5
- CLOUDSAT
- Dawn
- Deep Impact
- Genesis
- GOES (-P)
- GRAIL
- MAVEN
- MESSENGER
- Mars Global Surveyor
- New Horizons
- Mars Odyssey
- SDO
- OSIRIS-REx

Term Node 6
- Phoenix
- OCO-2
- InSight

Term Node 7
- KEPLER
- Swift
- GPM

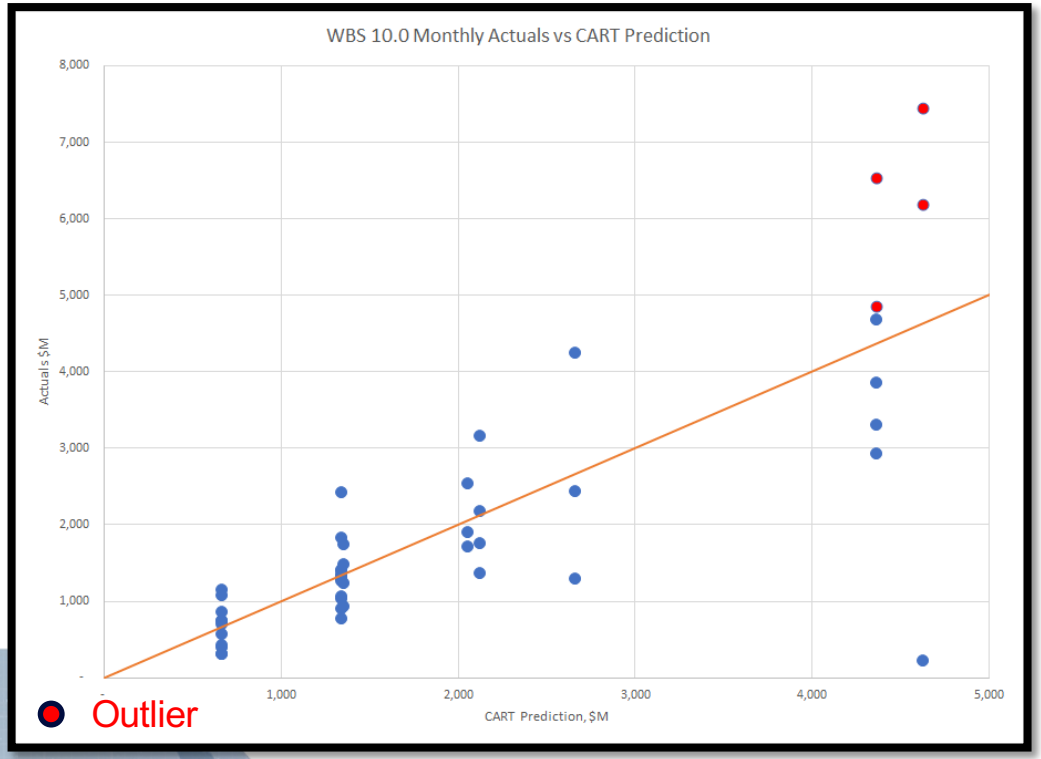
Term Node 8
- Cassini
- Juno
- MRO
- MSL*
- TDRSS K-L
- GOES-R*



- When the identified outliers are estimated with the PCEC v2.3 CER for I&T, a much higher level of error is observed

WBS 10.0 (I&T)	RMSE
PCEC v1	1,309
PCEC v2.3	753
CART - 1st Attempt	11,835
CART - 2nd Attempt	1,013

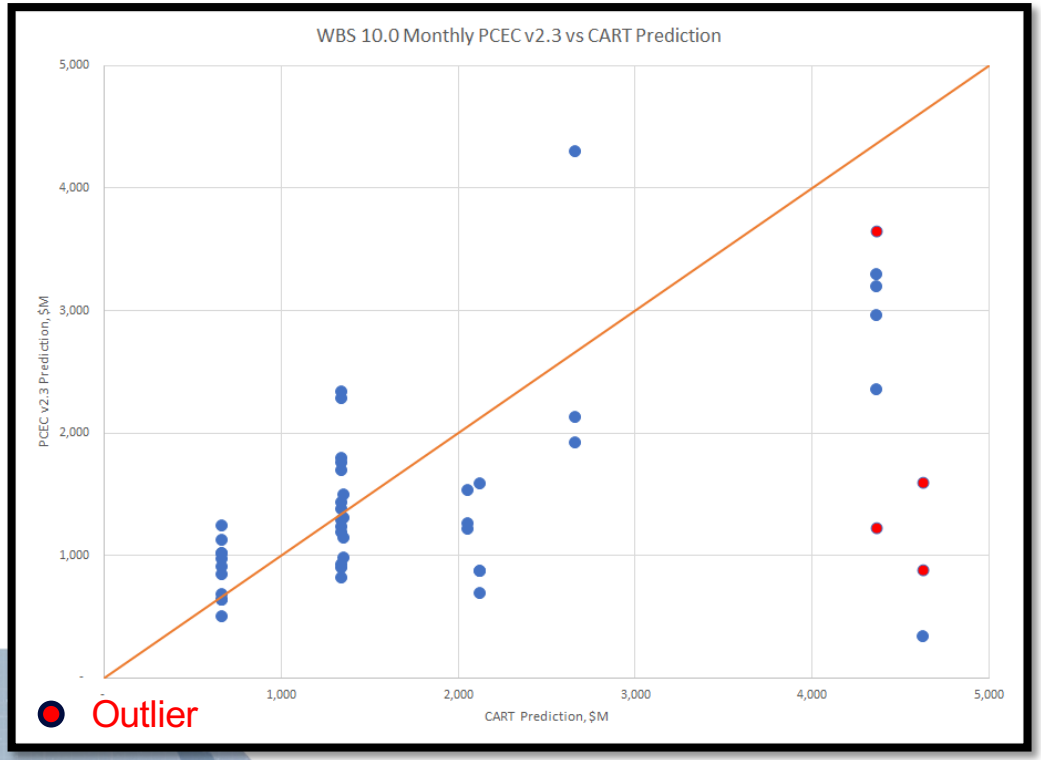
I&T PCEC v2.3 CER Performance Comparison



- The new CART generated CER for I&T maintains a similar level of error overall but also allows the identified outliers to be estimated with a higher degree of accuracy.

WBS 10.0 (I&T)	RMSE
PCEC v1	1,309
PCEC v2.3	753
CART - 1st Attempt	11,835
CART - 2nd Attempt	1,013

I&T CART Generated CER Performance Comparison



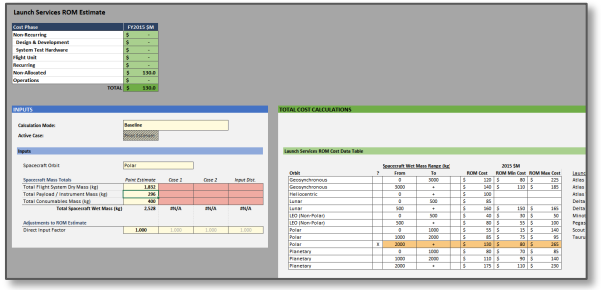
- In comparing the PCEC v2.3 predictions with the new CART predictions, it is clear that the CART approach results in higher I&T estimates for some missions which mostly have more complex I&T flows
- Initial K-fold cross validation of the CART CER indicates that the results may not be as robust as the traditional CER approach

WBS 10.0 (I&T)	RMSE
PCEC v1	1,309
PCEC v2.3	753
CART - 1st Attempt	11,835
CART - 2nd Attempt	1,013

Improving Performance for System I&T Estimates

- Continue to normalize new mission data as it becomes available
- Add new input parameters (e.g., payload metrics) that better capture the I&T trade space and develop new CERs as appropriate
- Develop an alternate CART based CER set
- Explore ways to use CART results to better inform input selection in the traditional CER development process

Robotic SC Future Plans

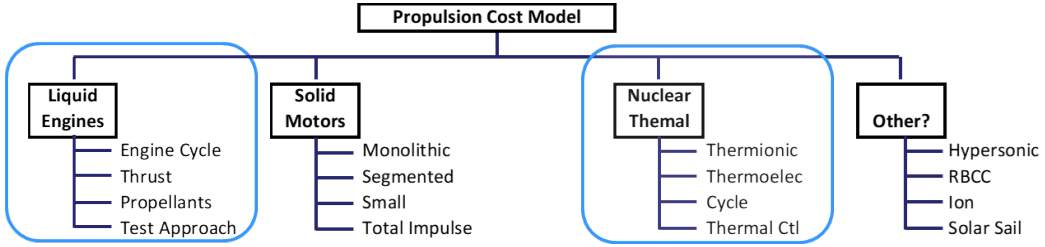


	Original	Added	TOTAL
GEO	60	11	71
Helio	3	6	9
LEO	10	6	16
Lunar	3	0	3
Non-Polar	0	2	2
Planetary	14	10	24
Polar	19	14	33
TOTAL	**109**	**49**	**158**

- **Launch Vehicle ROM:** A simple estimating worksheet for including a rough-order of magnitude launch vehicle cost into a science mission estimate
  - Initially added to PCEC in 2016 timeframe
  - Leverages total spacecraft wet mass and orbit destination to "select" a launch vehicle class
  - Not intended to take the place of an official LSP cost
- Recent data collection effort has been undertaken to update the dataset; 49 missions added to the database
  - LRD CADRe data for NASA missions
  - Publicly available sources for USAF, USSF, NRO, & USN
- Memo/Whitepaper under development to provide explanations of the research, normalizations, and analysis of source data
  - Source data to be available for internal NASA users

Launch Vehicle Catalog Update

- Propulsion Cost Model Updates



  - Liquid Rocket Engines (LRE) and Nuclear Thermal Propulsion (NTP) are ready for release (coming soon…mid-2022)
  - Solid Rocket Motor module under development
    - Existing NASA solids database analyzed (upper stages, kick motors, sounding rockets)
    - Data recently exchanged with Missile Defense Agency (MDA) regarding solids they have developed/procured; analysis is underway to incorporate
    - Estimating relationships will follow expanding on the SRM CER in CASTS

- SLS, Orion, ISS, and other misc. transportation vehicle data to be incorporated into CASTS CERs

CASTS Updates in Development

- A series of self-paced training modules are being developed as part of the CFOU Training Curriculum
- Modules 1, 2, and 7 are in work, with the goal of getting them reviewed and completed in 2022

Planned Module List (Apr 2022)

#	Module Title	Overview
1	**PCEC Overview**	A high-level summary of PCEC and the major elements that constitute the tool
2	**The PCEC Ribbon**	A review of each button on the PCEC Interface Ribbon and the associated dialog boxes that appear when clicked by the user
3	**PCEC Estimating Artifacts**	A walkthrough of all the different types of estimating artifacts/templates present in the Interface
4	**Building a PCEC Estimate from Start to Finish**	A walkthrough of how to create and edit a complete PCEC estimate file using the 'Launch an Estimate' routine and other Interface routines
5	**Sensitivity & Uncertainty Analysis in PCEC**	A detailed review of the different types of sensitivity and uncertainty analysis capabilities that are offered in PCEC
6	**Importing Custom CERs to the PCEC Interface**	An introduction to how to add custom CERs to a user's copy of PCEC
7	**PCEC Supporting Data & Documentation**	A guide to the documentation that NASA users can get access to understand more about PCEC

PCEC Path Forward

- Next update capabilities & timeline TBD (v2.3.1?)
  - Robotic SC model updates: I&T updates, guidance on outliers
  - Launch Vehicle Catalog updates
  - Linkages to the latest NICM, PCM (nuclear), MOCET
- Longer term items
  - Incorporation of additional missions into datasets, including accounting for COVID in normalizations
  - Continued evolution of Robotic SC estimating: outlier estimating, I&T CER updates, CART approach
  - Incorporation of results from new approaches and ongoing research

PCEC Email Contact:	MSFC-PCEC@mail.nasa.gov
Application Website(s):	ONCE Database (https://oncedata.hq.nasa.gov/) NASA Software Catalog (https://software.nasa.gov/) REDSTAR Library (https://sharepoint.msfc.nasa.gov/sites/redstar/)

Backup

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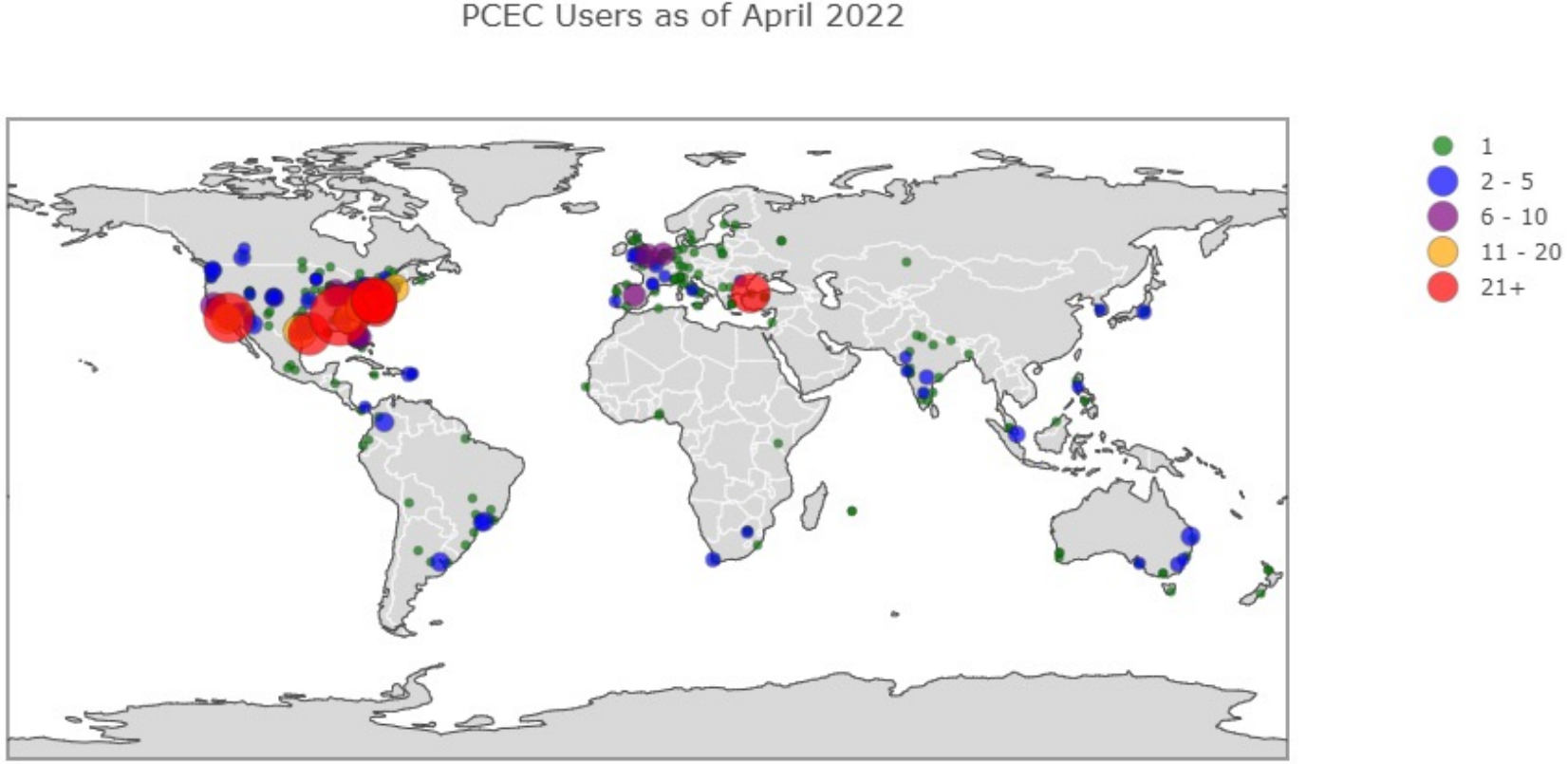
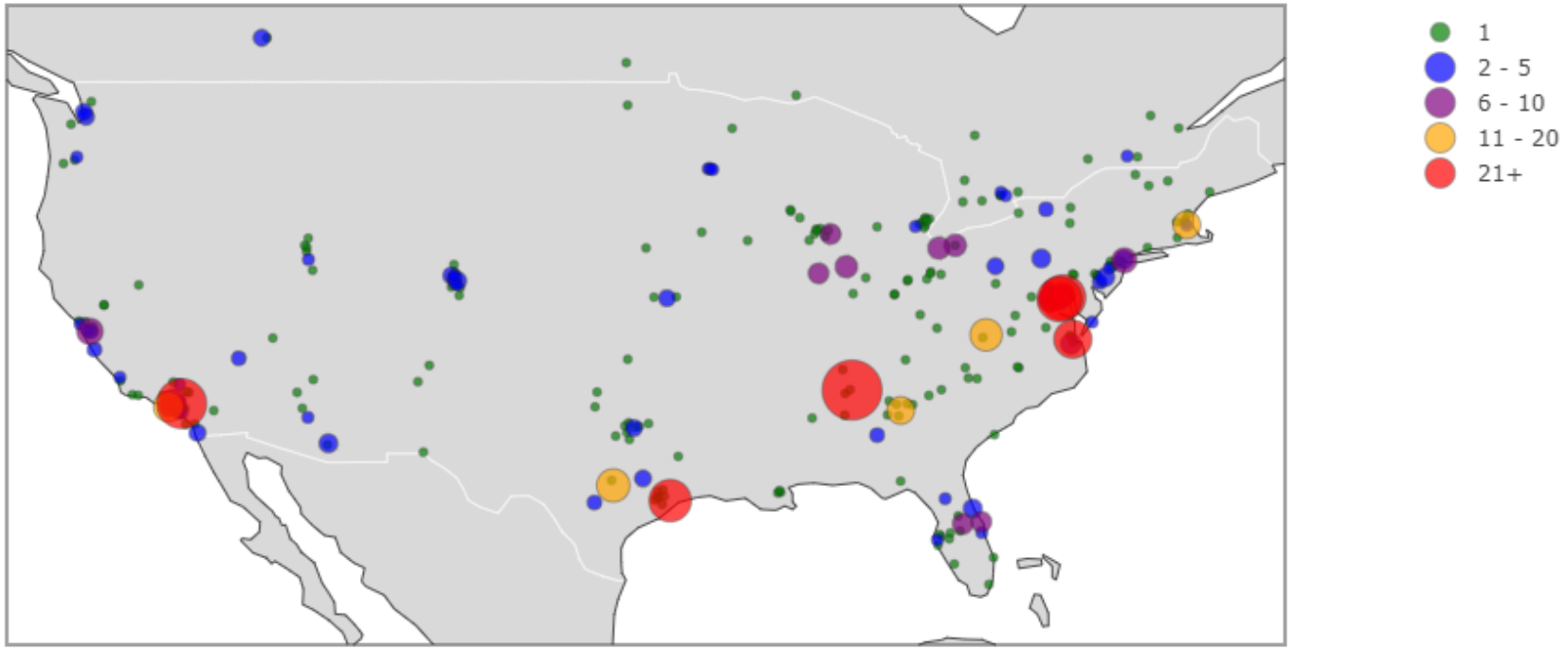


PCEC Download Distribution - April 2022

PCEC Users as of April 2022



PCEC Download Distribution - US - April 2022

- Larger, directed type missions were generally considered outliers in the PCEC v2.3 CERs
- CART analysis may make it possible for us to bring them back into the mix to provide more inclusive CERs
- The small end of the mission spectrum could also benefit, increasingly important as new CubeSat missions are being developed across NASA

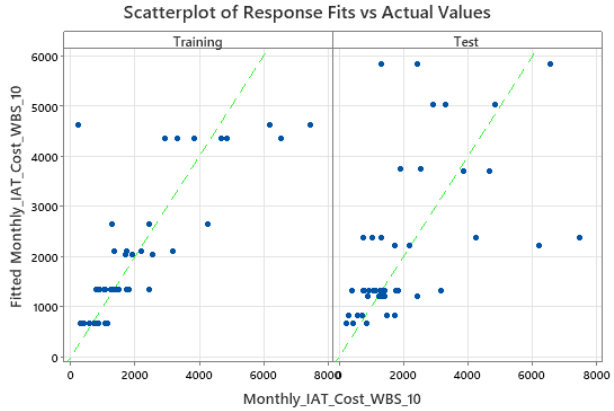
Data Set Outliers 11/04/2019															
Missions	*Count*	*STR_NRC*	*STR_RC*	*THM_NRC*	*THM_RC*	*PRP_NRC*	*PRP_RC*	*PWR_NRC*	*PWR_RC*	*CDH_NRC*	*CDH_RC*	*GNC_NRC*	*GNC_RC*	*TCM_NRC*	*TCM_RC*
Cassini	13	X	X	X	X		X	X	X	X	X	X	X	X	X
GOES-R	13	X	X		X	X	X	X	X	X	X	X	X	X	X
MSL-Rover	10	X	X	X	X				X	X	X	X	X	X	
GPM	5			X				X	X			X	X		
TDRSS K-L	5	X		X				X						X	X
SDO	4	X	X		X								X		
MSL-EDL	3	X	X										X		
LRO	2		X		X										
GOES-P	2											X	X		
MER-Cruise Stage	2			X	X										
MER-EDL	2	X	X												
MSL-Cruise Stage	2			X	X										
MESSENGER	1													X	
Spitzer	1										X				
Juno	1														X
MER-Rover	1									X					
MRO	1													X	
NEAR	1					X									
New Horizons	1						X								
VAP	1							X							
WMAP	1				X										
	Count	7	7	6	8	2	3	5	4	4	4	5	7	6	4

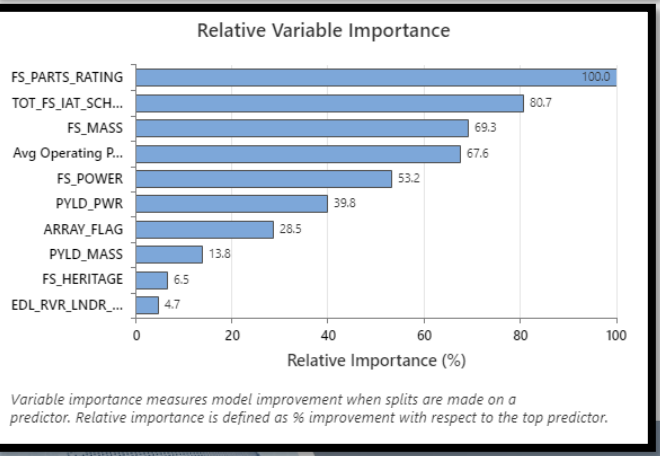
PCEC v2.3 Spacecraft Subsystem CER Outliers

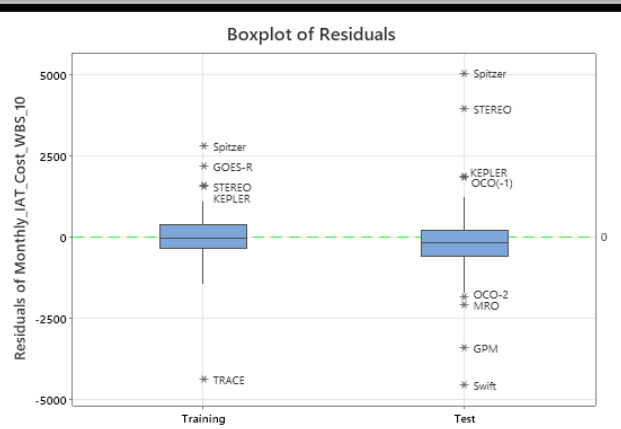
Model Summary

Total predictors	10
Important predictors	10
Number of terminal nodes	8
Minimum terminal node size	3

Statistics	Training	Test
R-squared	63.10%	17.32%
Root mean squared error (RMSE)	1013.2204	1516.6492
Mean squared error (MSE)	1.02662E+06	2.30022E+06
Mean absolute deviation (MAD)	601.9103	965.6494
Mean absolute percent error (MAPE)	0.7077	0.6486

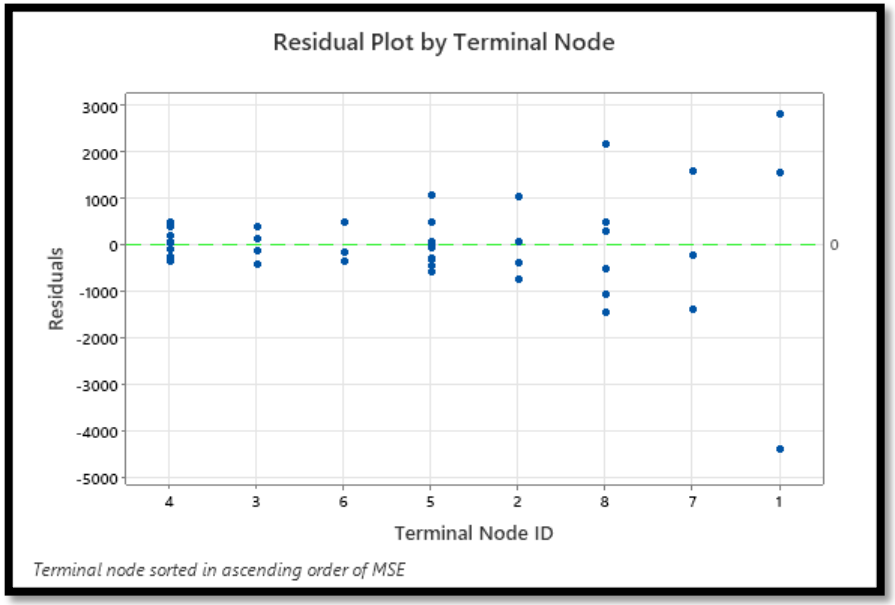






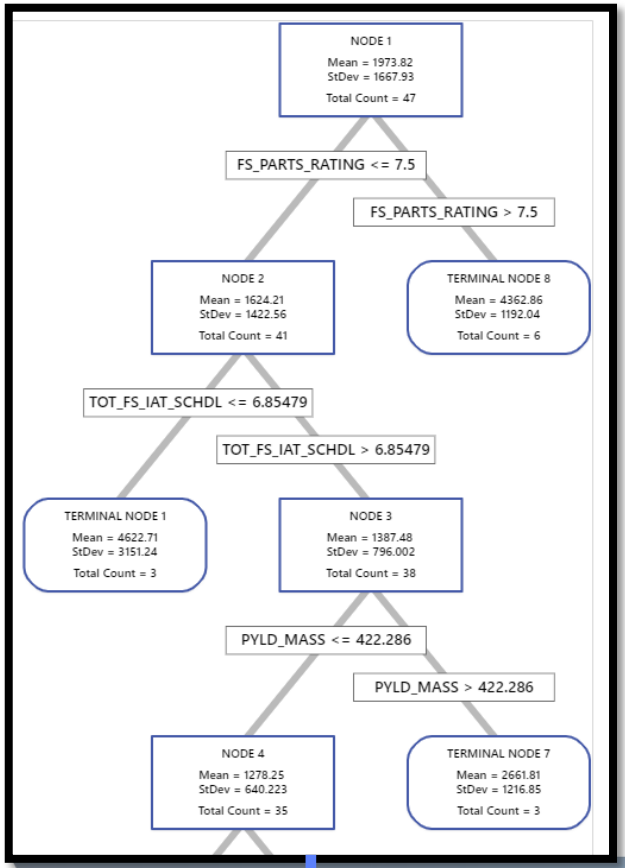
- Comparison of the test and training statistics indicate that the CART generated CER is likely not as robust as the PCEC v2.3 CER that was developed using traditional methods
- Adding additional missions to the data set may help make the CART approach more robust

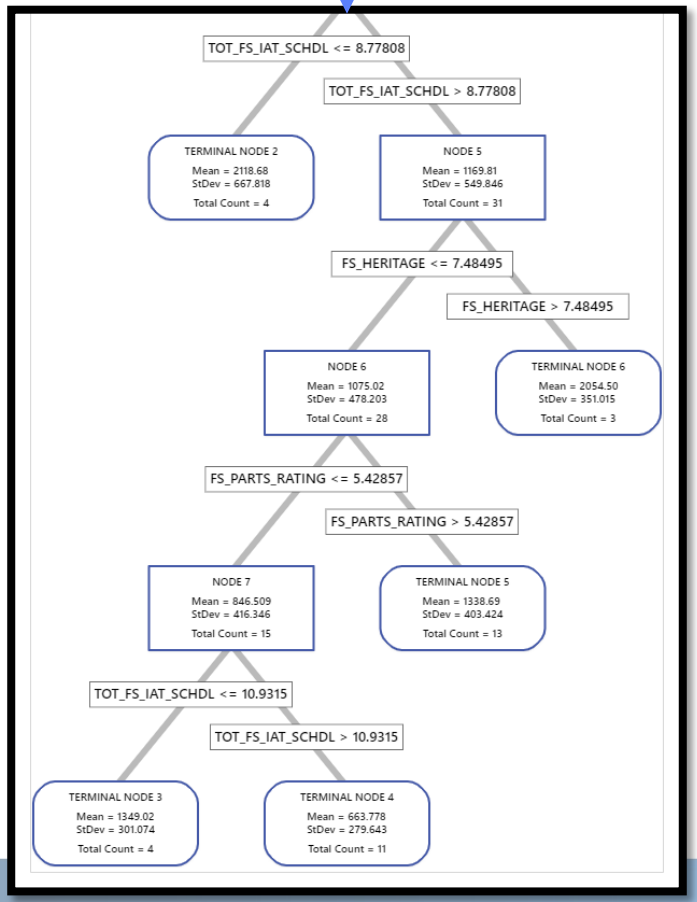
CART I&T CER (2nd Attempt) K-Fold Cross Validation



- There is a wide degree of variation in some of the tree nodes.
- The nodes with the larger spread tend to include the identified outliers and the larger, directed missions

CART I&T CER (2nd Attempt) - Residuals





CART I&T CER (2nd Attempt) – Zoomed In View