estimate

estimate • analyze • plan • control

Heuristics For A Space Technology Cost Estimation Model

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Outline of Topics

- Introduction to the problem
- Examples of current space technology projects
- Definition and criteria for heuristics
- Overview of current space project cost estimating heuristics
- Segue to parametric cost estimating
- Utilizing parametric cost models to estimate a ground based space technology development project

INTRODUCTION TO THE PROBLEM: EDISON AND THE LIGHT BULB

Edison and the Light Bulb

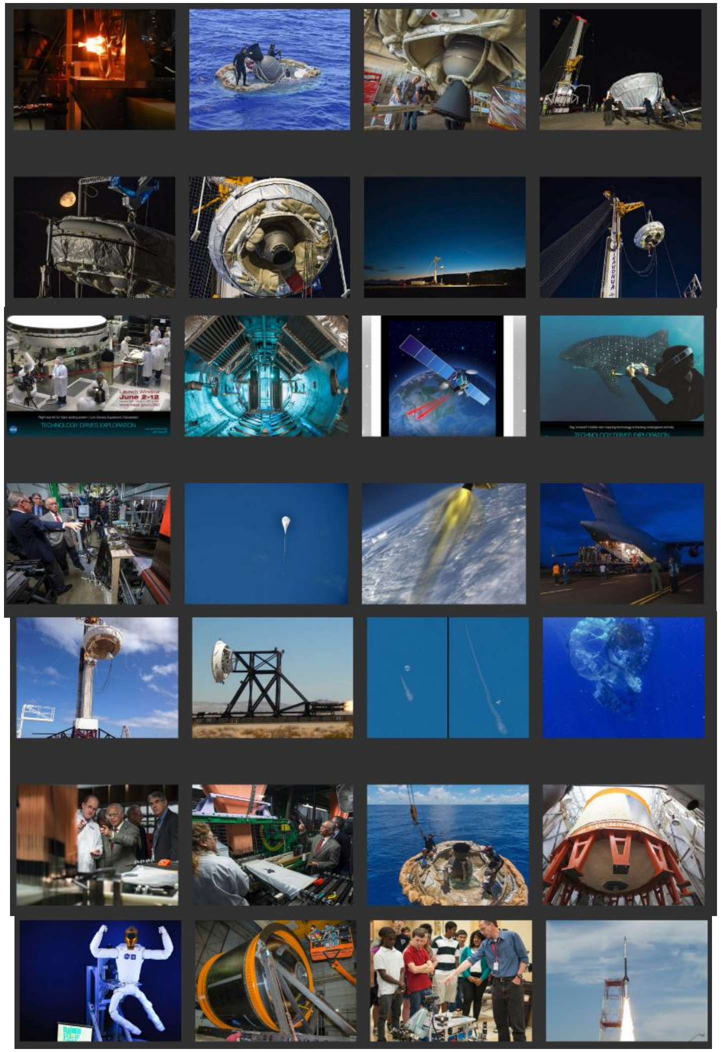
- Once there was a cost estimator working in Thomas Edison's Menlo Park Laboratory*
- Edison asked him to estimate how much it would cost to invent the light bulb
- The estimator…
  - Tallied the cost of glass blowing equipment to construct bulbs
  - Pumps to pull a partial vacuum inside the bulbs
  - A range of materials from which experimental filaments could be made
  - A low voltage electrical source
  - The rental cost of a laboratory in which to work
  - The cost of Edison and a small team of technicians to work for several months
- The project overran by a factor of 10
- That was in 1878; however, technology cost estimating is still done the same way today
- As a result, the cost estimates are still mostly always low

*Note: Some "artistic license" was employed in this account

EXAMPLES OF CURRENT SPACE TECHNOLOGY PROJECTS

Examples of Space Technology Development Projects

- Composite cryotank project
- Human robotic systems
- Solar electric propulsion
- Green propellants project
- Low density supersonic decelerators project
- Small spacecraft technology
- Sample return robot
- And many more



Images from NASA Space Technology Mission Directorate Website

Estimating the Cost of Technology

- Estimating the cost of technology maturation is normally done by …
  - Level of effort assumptions
    - *n* people working *m* months
    - Plus materials, purchased parts
    - Plus rental time for laboratories, equipment, test facilities, supercomputer time, etc.
    - **The same approaches used by Edison's cost estimator in 1878**
- Humans are notoriously inept in this sort of thing (optimism bias)
- This paper discusses other approaches:
  - Heuristics
  - Parametric approaches

DEFINITION AND CRITERIA FOR HEURISTICS

Heuristics

A heuristic is any approach to problem solving, learning, or discovery that employs a practical methodology not guaranteed to be optimal or perfect, but sufficient for the immediate goals.

Where finding an optimal solution is impossible or impractical, heuristic methods can be used to speed up the process of finding a satisfactory solution.

Examples of this method include using a rule of thumb, an educated guess, an intuitive judgment, stereotyping, profiling, or common sense. *(Wikipedia)*

Criteria for Developing Heuristics

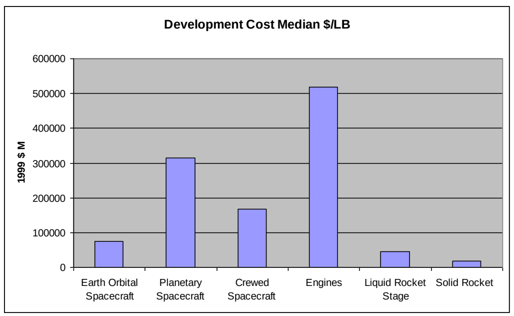
1. Agreement among experts that the heuristic is useful and correct
2. Heuristic must stand the test of time
3. Heuristic must be resilient across different scenarios
4. Heuristic must demonstrate value by…
   a. Re-occurring more than once
   b. Not be considered obvious by everybody, particularly people who are new to the field

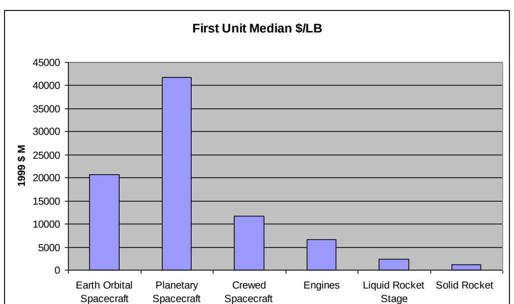
From Heuristics for Systems Engineering Cost Estimation
14th Annual PSM Users' Group Conference New Orleans, LA
Dr. Ricardo Valerdi
Massachusetts Institute of Technology
July 27, 2010
(Dr. Valerdi is now with the University of Arizona)

OVERVIEW OF CURRENT SPACE PROJECT COST ESTIMATING HEURISTICS

Some CERs/Heuristics For Full Scale Development of Space Projects

Project Class	Development Cost Per Pound						First Unit Production Cost Per Pound					
	n	Mean	Median	StdDev	Min	Max	n	Mean	Median	StdDev	Min	Max
Earth Orbital Spacecraft	**68**	**$107,208**	**$75,785**	**$88,454**	**$13,587**	**$439,254**	**68**	**$24,584**	**$20,668**	**$21,003**	**$3,891**	**$147,193**
Communication	20	$147,452	$147,868	$80,648	$22,809	$310,854	20	$31,245	$28,486	$17,205	$3,891	$78,840
Mapping/Meterological	7	$95,966	$62,688	$83,342	$25,415	$272,481	7	$17,824	$15,998	$6,644	$9,911	$26,417
Observatory	6	$44,586	$45,580	$22,015	$18,027	$70,436	6	$11,555	$12,071	$4,430	$4,908	$17,024
Positioning/Navigational	3	$163,807	$125,751	$167,932	$18,169	$347,502	3	$19,058	$14,454	$17,249	$4,514	$38,114
Reconnaissance	5	$138,506	$89,791	$98,684	$43,701	$265,789	5	$28,219	$35,493	$15,184	$10,868	$44,284
Science	27	$82,144	$62,441	$81,550	$13,587	$439,254	27	$24,240	$17,167	$27,502	$4,655	$147,193
Planetary Spacecraft	**21**	**$402,625**	**$313,975**	**$396,249**	**$54,286**	**$1,767,527**	**21**	**$55,450**	**$41,825**	**$46,751**	**$7,072**	**$221,333**
Inner Planetary	4	$352,495	$174,099	$432,357	$66,381	$995,399	4	$28,980	$30,279	$17,434	$7,072	$48,289
Outer Planetary	11	$364,028	$356,403	$203,321	$54,286	$707,699	11	$59,056	$59,076	$27,596	$23,102	$114,223
Planetary Lander	3	$824,135	$610,948	$856,924	$93,930	$1,767,527	3	$109,294	$78,070	$100,146	$28,480	$221,333
Probe	3	$189,481	$204,057	$29,075	$156,001	$208,386	3	$23,678	$27,399	$15,094	$7,072	$36,564
Crewed Spacecraft	**8**	**$240,780**	**$167,584**	**$246,091**	**$29,996**	**$735,638**	**8**	**$18,776**	**$11,737**	**$21,926**	**$2,263**	**$70,973**
Engines	**21**	**$517,323**	**$518,095**	**$532,302**	**$45,013**	**$2,056,478**	**21**	**$11,545**	**$6,639**	**$14,633**	**$551**	**$52,083**
Liquid Rocket Stage	**8**	**$60,608**	**$45,557**	**$78,241**	**$11,013**	**$248,889**	**8**	**$4,026**	**$2,432**	**$3,060**	**$1,150**	**$8,875**
Solid Rocket	**3**	**$53,685**	**$17,202**	**$78,149**	**$449**	**$143,404**	**3**	**$2,645**	**$1,126**	**$3,630**	**$21**	**$6,788**





- All cost are in millions of 1999 dollars; weights are dry mass in pounds
- Costs include prime contractor overhead and G&A but exclude fee
- Costs exclude government support costs which can add 5% to 20% depending upon the complexity of the project
- Development cost includes all full scale development expenditures including design activities, test hardware and testing, ground support equipment required by the prime and management and systems engineering activities
- First unit production costs includes fabrication including recurring management and systems engineering activities

Source: Rules of Thumb: Acquisition Cost Dollars Per Pound Ranges for Various Classifications of Space Projects by Joe Hamaker, NASA Marshall Space Flight Center, July 2001

Heuristic CER Slopes (Cost = Mass^b)

NAFCOM Assumed Slopes

"b" values

	DDT&E	FU
Antennas Subsystem	0.85	0.80
ASE	0.55	0.70
Attitude Control/Guidance and Navigation Subsystem	0.75	0.85
Avionics Group	0.90	0.80
CC&DH Group	0.85	0.80
Communication Subsystem	0.85	0.80
Crew Accommodations	0.55	0.70
Data Management Subsystem	0.85	0.80
ECLS Subsystem	0.50	0.80
Electrical Power and Distribution Group	0.65	0.75
Electrical Power Subsystem	0.65	0.75
Instrumentation Display & Control Subsystem	0.85	0.80
Launch & Landing Safety	0.55	0.70
Liquid Rocket Engines Subsystem	0.30	0.50
Mechanisms Subsystem	0.55	0.70
Miscellaneous	0.50	0.70
Power Distribution and Control Subsystem	0.65	0.75
Propulsion Subsystem	0.55	0.60
Range Safety	0.65	0.75
Reaction Control Subsystem	0.55	0.60
Separation	0.50	0.85
Solid/Kick Motor Subsystem	0.50	0.30
Structure Subsystem	0.55	0.70
Structures/Mechanical Group	0.55	0.70
Thermal Control Subsystem	0.50	0.80
Thrust Vector Control Subsystem	0.55	0.60

Other Factors Affecting CER Slopes for Mass Driven CERs

Consideration	Development CER Slope	Unit Production CER Slope
As the content of electronics and software increases…	Higher slope	Higher slope
As the level of design repeat or replication increases…	Lower slope	Higher slope
As the level of design heritage and/or Technology Readiness Level (TRL) increases…	Lower slope	Lower slope
As the level of automation increases…	Higher slope	Lower slope

Other Factors Affecting Slope

From "A Monograph On CER Slopes, Joe Hamaker, August 2013, NASA Cost Analysis Symposium, NASA Jet Propulsion Laboratory (JPL).

Heritage and Technology Readiness

TRL Rating	TRL Description	Degree of New Design Cost Factor: Existing Design (0.2)*	Minor Mod (0.4)	Significant Mod (0.6)	Major Mod (0.8)	All New (1.0)	
1	Basic principles observed and reported	NA	NA	NA	NA	3.7	1.3$^{(6\text{-}TRL)}$(Home Base Cost Factor)
2	Technology concept and/or application formulated	NA	NA	NA	NA	2.9	
3	Analytical and experimental critical function and/or characteristic proof-of-concept	NA	NA	NA	NA	2.2	
4	Component and/or breadboard validation in laboratory environment	NA	NA	NA	NA	1.7	
5	Component and/or breadboard validation in relevant environment	NA	NA	NA	NA	1.3	
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	"Home Base" row
7	System prototype demonstration in a space environment	0.20	0.40	0.60	0.80	1.00	
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	0.20	0.40	0.60	0.80	1.00	
9	Actual system "flight proven" through successful mission operations	0.20	0.40	0.60	0.80	1.00	

Red zone: Under normal circumstances projects would not begin development prior to achieving TRL 6
Red zone New Design Cost Factors in All New column represent approximate penalty for starting development prior to TRL 6
Red zone New Design Cost Factors in <All New column are nonsensical (<TRL 6 implies All New)

Green zone: Normal "field of play" for projects
Green zone New Design Cost Factors represent range of possible new design given that technology is "ready" (see example below)

Example:

Envision a new upper stage that requires a new propellant tank.
Assume the stage is a different size than any that exist but is within the range of previous tanks--thus the tank is of a size never built before also.
Assume the propellant tank for the stage is to be constructed from Al-Li using standard pressing, rolling, bending and milling procedures for Al-Li.
Assume the tank sections will be joined using standard friction stir welding techniques.
Assume that the engineering and manufacturing workforce is experienced on previous tanks using the above approachs.
Therefore, it seems the *technology* to make this tank is well within our grasp.
If some specific design work has been done on this specific tank, the degree of new design required could be <1.0.
But if no specific design work has been done on this specific tank, the degree of new design required could be 1.0.

***Existing design set at 0.2 to reflect engineering work associated with qual/integration/verification effort needed to utilize an existing design**

From "Some Thoughts on Cost Estimating Technology Readiness Levels"
Workshop on Assessing Technology Maturity; NASA NET Program
Tyson's Corner VA; September 18, 2003 by Joe Hamaker

SEGUE TO PARAMETRIC COST ESTIMATING

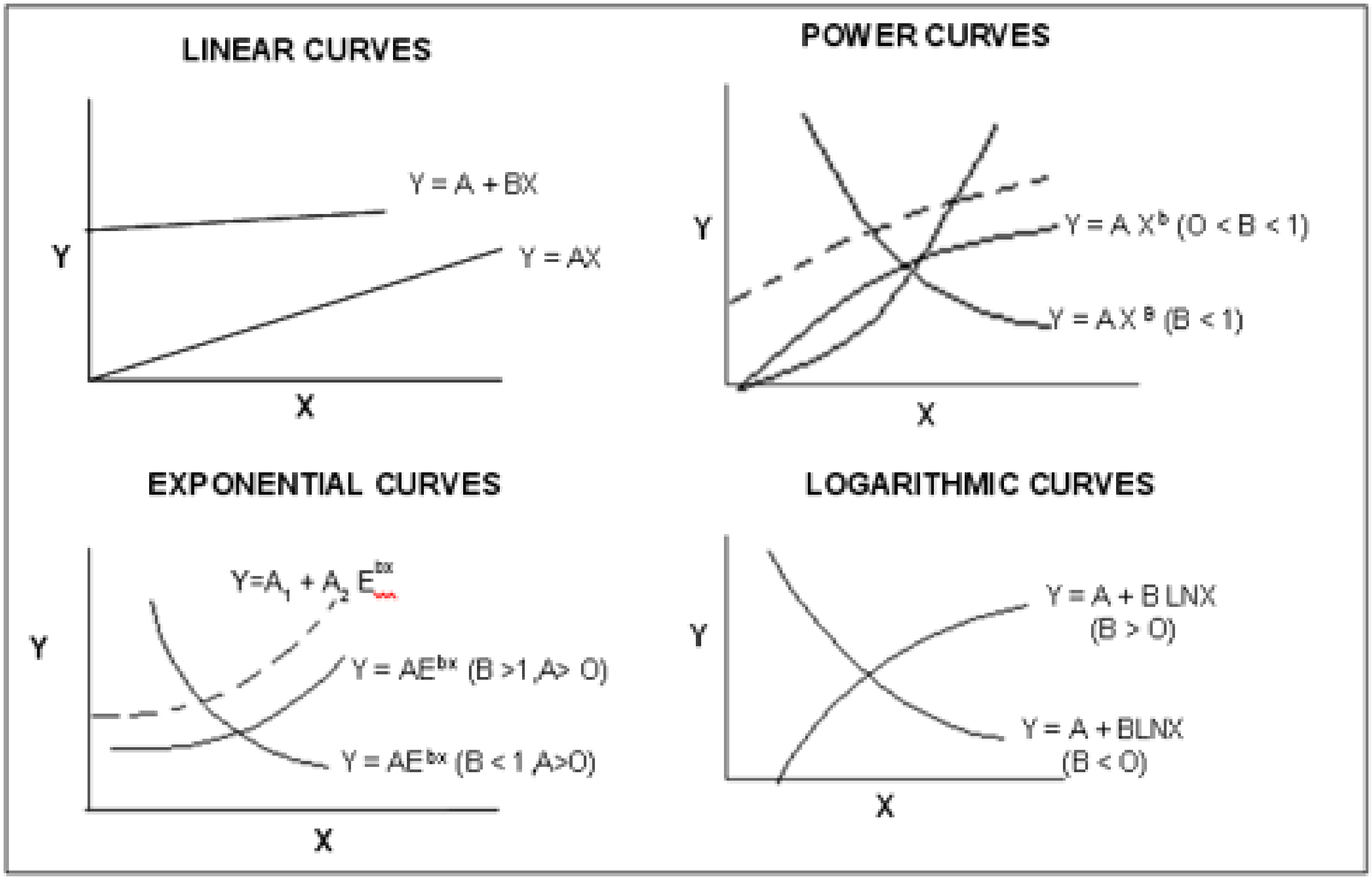
Segue to Parametrics

- The preceding space project cost estimating heuristics were examples—existence proofs—that space cost estimating heuristics are common
- But most of what is out there is more appropriate for full scale development projects
- But we will now use that base to segue into a much more formal arena of cost estimating—parametric cost models—in the attempt to get to something really useful for estimating the cost of space technology development projects

Parametric Cost Estimating

- Parametric cost estimating uses cost estimating relationships (CERs) to estimate the cost of a product, project or activity
- Parametric models use both formal CERs derived from historical data and heuristically developed relationships
  - Sometimes "teased" out of historical cost records as well as observed experiences by cost estimators
  - Sometimes supplied by Subject Matter Experts
- Parametric cost estimating translates descriptive attributes (e.g. mass, dimensions, volume etc.), performance characteristics (speed, range, thrust, design life) into cost

Cost Estimating Relationships (CERs) Common Forms



UTILIZING PARAMETRIC COST MODELS TO ESTIMATE A GROUND BASED SPACE TECHNOLOGY DEVELOPMENT PROJECT

SEER Models for Space Cost Estimating

SEER by GALORATH

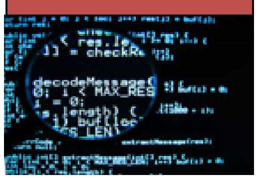
Electro Optical Systems

Optics, Detectors, Coolers, Calibrators, EOS Mechanism, Laser, Optical Bench

Integrated Circuit

FPGAs, Custom ICs, RFICS, ASICS

SEER for SW



Payload and Spacecraft Software

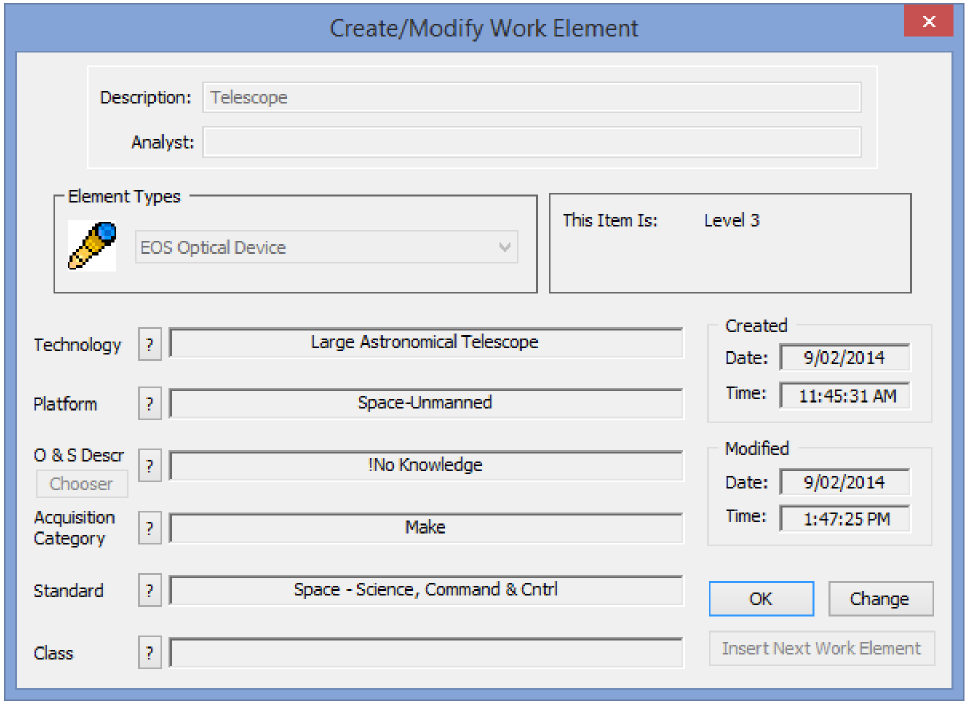
SEER for HW

Mechanical Systems, Structures, Mechanism, Bus components, Electromechanical Electronics. Also used to calculate Program Management, Systems Engineering and Mission Assurance at rollup levels.

NASA WBS Covered	
1,2,3	PMSEMA
5	Payload
6	Spacecraft
10	System Integration

Knowledge Bases

- SEER-H uses *knowledge bases* to derive and **preset** initial parameter settings based on industry experience
- Choose knowledge bases for:
  - **Application** (Large Astronomical Telescope, Laser, Cryocooler, Transponder, etc.)
  - **Platform** (Space-Manned, Space-Unmanned, Ground Fixed, etc.)
  - **Acquisition Category** (Build to Print, Buy & Integrate, Make, Modification, etc.)
  - **Standard** (Commercial, Military, Space, etc.)
  - **Operations & Support** (Remove Replace, Repair, Scheduled Maintenance, etc.)
- Users may add their own knowledge bases if desired



Utilizing a parametric cost model to estimate a ground based space technology development project

- The SEER-H knowledge base selection (from the previous chart) of most utility for our subject today is the **Platform factor**
- We can use the Platform factor to calibrate an existing full scale development product and then change the Platform to Ground-Fixed to estimate the cost of a ground based technology project
- Many other factors would also be re-set to hone in on a reasonable estimate of our ground based technology product:
  - Acquisition category (technology maturity)
  - Weight
  - Material composition
  - Complexity of form/fit
  - Standards
  - Etc.

Knowledge Bases

Platform: Electronics, Mechanical/Structural, and Site

Platform knowledge bases can be selected for electronic, mechanical and site work element types.

Knowledge Base	Description
Air-Manned	Manned airborne systems such as fixed-wing aircraft, rotorcraft used for military, research, civil or commercial purposes.
Air-Unmanned	Unmanned airborne systems, including UAVs, aerostats.
Consumer	Intended for commercial applications, typically home or business use.
Ground-Fixed	Any immobile terrestrial non-commercial product, including antenna dishes, buildings, bridges. Fixed land-based systems.
Ground-Mobile	Mobile land-based systems, including trucks and trains.
Industrial	Intended for use in an industrial environment.
Missile	A powered munition whose trajectory is at least in part controlled by an internal guidance system. May or may not have a capability for sustained level flight.
None	No selection of a Platform knowledge base.
Sea	Surface sea-based systems, including naval and commercial ships.
Space-Manned	Manned space systems, including the Space Shuttle, manned additions to it, or manned equipment certified for linkage with it, for example, The International Space Station.
Space-Unmanned	Unmanned space systems, including telecommunications and remote sensing satellites, and exploratory vehicles intended for interplanetary and other flight paths.
Submersible	Submersible sea-based systems, including military submarines and commercial submersibles.

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