Appendix K: Schedule Estimating Relationship (SER) Development and Model Inputs

There is a fundamental relationship between project schedule behavior and project cost behavior. Understanding this relationship is essential to the cost estimator. The following topics are described in this appendix:

K.1. Background

There is a fundamental relationship between project schedule behavior and project cost behavior. Understanding this relationship is essential to the cost estimator. While this cost and schedule relationship seems intuitive to those in project management, it is often difficult for an estimator to quantify or model for the purposes of analysis. To complicate matters further, there is a distinction between the relationship of cost and schedule and the correlation between cost growth and schedule growth. The former (relationship of cost and schedule) is not always obvious, whereas the latter (correlation of cost growth and schedule growth) is mostly self-evident. For example, it is widely observed in a multitude of programs and projects that schedule growth usually leads to cost growth. In addition, the integrated master schedule needs to correspond to cost estimates to ensure that enough resources can be applied to activities to complete them within the expected duration. This should be done before the project schedule is finalized so that the relation between accurate cost and schedule estimates can be verified.

Ascertaining specific values of correlations for a particular project is a challenge. As with Cost Estimating Relationships (CERs), there are quantifiable relationships between the schedule and other project factors and influences. Schedule Estimating Relationships (SERs) can likewise be used to estimate durations of schedule events much like CERs are used to estimate a particular price or cost.

SER is a technique used to estimate schedule duration by connecting an established relationship with one or more independent variables to the duration time of an event. If an independent variable (driver) demonstrates a measurable relationship with schedule duration, an SER can be developed. While relatively simple in concept, the ability to get accurate and meaningful data that can be used to quantify a relationship between an independent variable and schedule duration can be difficult.

This appendix provides a basic overview of NASA schedule estimating. Additional information on the subject is available in the NASA Schedule Management Handbook.[1]

K.2. NASA Experience and Usage

NASA's SER experience has been confined to the project level (spacecraft, vehicle, and major element), where analysis of aerospace projects moving from major milestones can be accomplished without the influence of lower-level distortions. This high-level analysis has yielded statistical data and some observable trends. A transition from study to implementation has begun recently with analysts using SERs, schedule data, and models to complete schedule risk analyses on programs and projects.

While CERs can be directly used in project cost estimation, SERs do not have the same direct applicability to schedule estimation as their cost counterparts. For example, while requirements affect both cost and schedule, changes in requirements do not affect both cost and schedule estimates equally. In many cases, this is primarily because of the immaturity of SER usage within NASA and the estimating community. SERs, for the most part, are not as well publicized or used for schedule estimation. This means that many analysts may not know that SERs exist or know whether they are applicable to their particular program or project. Schedule estimation itself is also relatively new at NASA, and conducting a risk analysis on schedule, where an SER would be used, is still not a common type of analysis performed by programs or projects. Nevertheless, the new policies regarding high and low estimates of cost and schedule, as well as a greater push to understand schedule, have led to an increase in the amount of schedule analyses completed at the Agency.

CERs and SERs share similarities. Although CERs do not typically have schedule as an input, the same *factors* usually drive project CERs and SERs. These factors could be technical, such as mass and power, or they could be programmatic, such as funding stability and international partnerships. This speaks to the fundamental and intuitive notion of the common relationship between cost and schedule within an effort, since the same factors are often used to estimate both cost and duration.

K.3. Project Schedule Analysis Methods

Parametric, analogy, and bottom-up estimating methodologies used in cost estimating are also applicable to schedule estimating. Estimating methods for schedule can be built using historical datasets, comparison to analogy, or detailed grassroots analysis. Estimating schedule durations can be extremely useful at both a high summary level or at the low activity level. The development of SERs, models, and logically linked schedules is a key component of schedule estimating. The level of detail selected will influence all of these key components. The selection of the schedule estimation method is tied to the relationship between cost and data availability, estimate purpose, data maturity, and program maturity levels. See Appendix C for more details.

K.3.1. Parametric Schedule Estimating

[1] http://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf

Estimating schedule using a parametric approach involves the same fundamentals as estimating cost. Schedule duration data and independent variables are collected to conduct data analysis and determine if there are statistically significant relationships present to produce a SER. SERs can contain many of the same independent variables as CERs but could also be based on different datasets, normalization techniques, or analysis methods.

K.3.2. Analogy Schedule Estimating

The analogy method for schedule estimating focuses on comparing the estimated duration with actual schedule data of similar missions. As with the analogy method for cost, careful consideration should be given to selecting the analogies. Any adjustments, deviations, or differences should be clearly identified and documented.

K.3.3. Engineering Build-Up/Grassroots Schedule Estimating

Using a detailed engineering build-up estimate to develop a schedule estimate is a common technique employed by program managers all over the world. A highly detailed and logically linked schedule is the standard product generated by this schedule estimation method. As with cost estimating, grassroots estimating for schedule requires the same strong attention to detail to be successful. Analysts should continue to be careful when differentiating between a build-up schedule estimate and a given detailed schedule plan. Both may employ the engineering build-up/grassroots approach; however, there are significant differences. The former reflects an attempt to capture the entire work effort to analyze durations and the program plan. A build-up schedule estimate, similar to cost, is an attempt to predict the actual (i.e., actual duration/actual finish date.) The latter reflects the result of a detailed project plan and may contain significant constraints, optimism, or undocumented assumptions. The plan duration and plan finish date from a given detailed schedule plan are attempts to organize future work with the goal of delivering on time.

Collected data need to be normalized. Normalization involves analyzing the raw data and making adjustments for consistency. The inconsistencies that may be found in a dataset include changes in dollar values over time (inflation); learning or cost improvements for organizational efficiency; and, if more than one unit is being produced, the effects of production rates on the dataset being analyzed.

When analyzing a dataset, normalization considerations should include adjustments for the cost (currency, Base Year), size and weight, complexity or mission, frequency, and mission platform (crewed, robotic).

K.4. SER Data, Databases, and Models

The underlying data that support the development and use of SERs are just as important as the data that support the development and use of CERs. The challenge at NASA is that these data are not as well recognized or available as similar cost data. Fortunately, recent efforts have begun collecting, organizing, and using schedule data to develop SERs for NASA analysts. This will result in the creation of new schedule estimating tools, as well as the expansion of existing cost models into the schedule estimating arena. Existing cost estimating models and tools such as the NASA Air Force Cost Model (NAFCOM[2]) also contain schedule data and SERs that can be used effectively, if the purpose and utility of the results are understood by the analyst. Refer to Appendix E for a summary of Agency-provided, as well as NASA-licensed models and tools. The following sections describe several of the SER-related tools used by the NASA community.

[2] See the NAFCOM version 2011 Help file, located under “Process-Based Schedule.”

K.4.1. NAFCOM Model

PCEC replacing NAFCOM

At the time of publication, NAFCOM is still heavily used by the NASA cost estimating community. However, NAFCOM users are in the process of transitioning to the Project Cost Estimating Capability (PCEC), which contains additional information and tools. PCEC incorporates NAFCOM models, as well as models developed by various NASA Centers and directorates. Since most users at this time are more familiar with NAFCOM, this handbook will continue to reference it. The expectation is that the functionality provided to users by NAFCOM and referred to here will continue with PCEC. See Appendix E for additional information on PCEC.

NAFCOM is perhaps the most widely used cost modeling tool that can provide schedule output to the user. Three levels of schedules are generated by NAFCOM: system level by stage, stage level by subsystem, and subsystem level by process. The term “stage” refers to a major element of a launch vehicle estimate, as in a two-stage or three-stage launch vehicle. Earth-orbiting and planetary missions typically do not have stages, so this level of the Work Breakdown Structure is not used. The process-based view inside of NAFCOM provides estimated average schedules at the process level for each subsystem and system integration element. The user can click on any of these process bars and view a further breakdown of the processes required to develop and produce the hardware element. Summary schedules are also provided in NAFCOM at the major system element level, broken out by subsystem and system integration element, and at the complete system level, broken out by major system element. The schedule is estimated using the launch year (provided by the analyst on the Global input screen) as the end date. The model uses a combination of cost and technical parameters to estimate the schedule durations for each of the subsystems and system integration elements. In the current model version, users cannot alter schedule durations or determine schedule penalties or benefits—only average schedules are provided.

The NAFCOM-process-based schedule results are primarily useful as a crosscheck of the project schedule assumptions across the major milestone events. The utility of these NAFCOM schedule estimates and their results can be seen as a part of the wider context of schedule metrics that provide comparison to project planning and assumptions. Since the results provided by NAFCOM are average schedules, they are best used as a crosscheck at a high level against the program plan. This is much like other professional scheduling rules of thumb anchored by technical experience. The schedule metric informs project managers about how their baseline plan compares to the historical data at a high level. Schedule metrics, such as those from NAFCOM, can be used to compare against the results of project planning efforts (outputs), as well as assist technical experts during the buildup of an initial estimate. NAFCOM also provides a schedule database that can be used to better understand the schedule data for particular programs and projects. Figure K-1 provides an example schedule output from the NAFCOM model at the subsystem level.

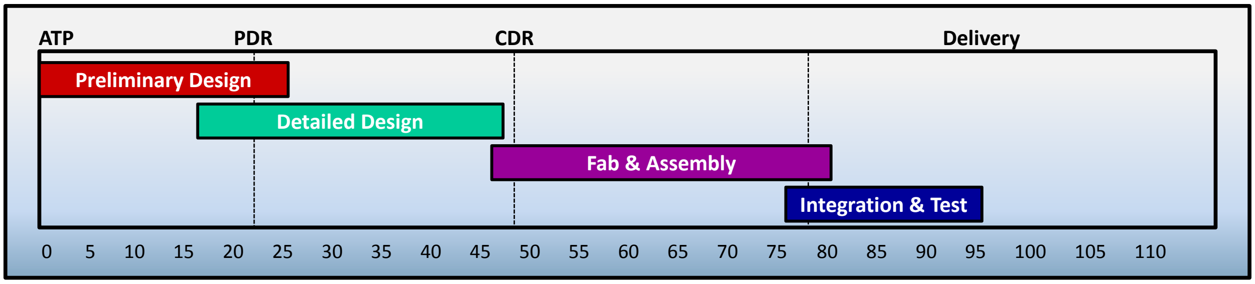
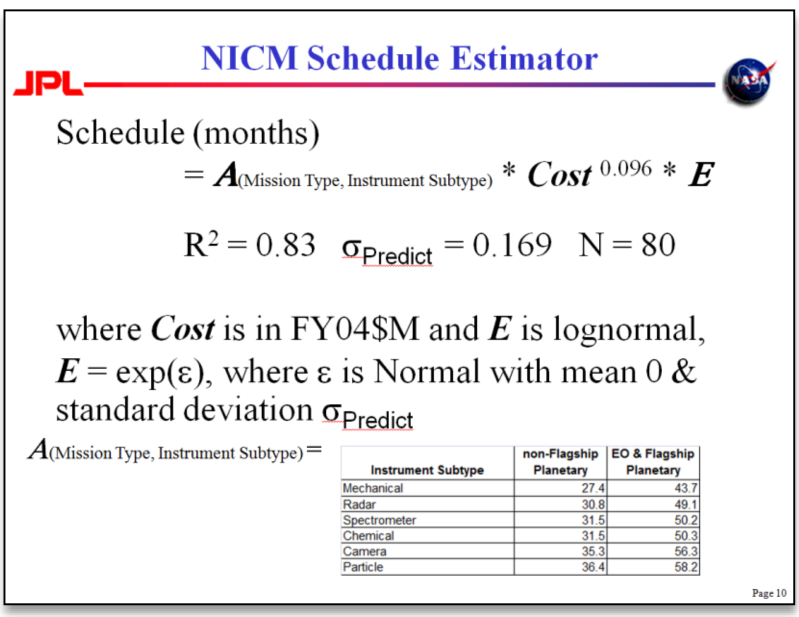


Figure K-1. An Example Schedule Output from NAFCOM at the Subsystem Level

Questions about NAFCOM should be directed to Andy Prince at *andy.prince@nasa.gov*.

K.4.2. NICM Model

Another NASA modeling tool that contains schedule data and SERs is the NASA Instrument Cost Model (NICM).[3] The NICM, which is available via the ONCE Model Portal at www.oncedata.com, focuses specifically on instrument estimation and contains a large database of many different types of instrumentation. This database includes schedule data, and there is a component within NICM for estimating schedule duration using SERs. The NICM approach to calculating duration from SERs is unique in that cost is an input to the SER equation. In this way, NICM SERs establish a functional link between the calculated cost of an instrument and its schedule duration. In addition to utilizing Cost As an Independent Variable (CAIV), NICM relies on the mission type and instrument subtype in the SER equation. Figure K-2 shows the NICM model schedule equation.



Instrument Subtype	non-Flagship Planetary	EO & Flagship Planetary
Mechanical	27.4	43.7
Radar	30.8	49.1
Spectrometer	31.5	50.2
Chemical	31.5	50.3
Camera	35.3	56.3
Particle	36.4	58.2

Figure K-2. NICM SER Information

Analysts with questions about using the NICM for SER capability should contact Joe Mrozinski of the NICM development team at the Jet Propulsion Laboratory (JPL), at *jmrozins@jpl.nasa.gov*.

[3] NICM version VI, Jet Propulsion Laboratory, May, 2014. For more information, see Appendix E.

K.4.3. QuickCost Model

The QuickCost[4] model developed by Joe Hamaker also contains a schedule database and SERs. The QuickCost schedule database contains duration data on satellites, engines, module and transfer vehicles, and experimental vehicles (X-vehicles). SERs are available primarily for satellites. QuickCost will calculate duration for X-vehicles and module and transfer vehicles, but this relies upon the SER developed for satellites with additional calibration. QuickCost SERs focus on providing duration results for Phases C and D, omitting duration for Phases A and B. Analysts seeking to use QuickCost for its SER capability should contact Hamaker for more information.[5]

K.4.4. Schedule Estimating Relationship Risk Assessment (SERRA)

The SERRA modeling tool also contains a database and SERs that can be used to conduct schedule risk analysis.[6] The SERRA SERs leverage the NAFCOM database of technical dependent factors with the explicit intent of generating NAFCOM-like SERs. SERRA can provide SERs and data on planetary, Earth-orbiting, and launch vehicle/human-exploration missions. SERRA was developed for NASA by SAIC and contains data on approximately 80 past projects. The available SERs can provide results for both Phase B/C and D and can provide a good crosscheck at a system level.

SERRA also provides schedule risk analysis through two components: technical uncertainty of inputs to the SER, and the error inherent in the SER regression. The underlying statistics of the SERRA SERs and additional information can be provided by CAD. The SERRA model is available at no cost for NASA Government distribution through the NASA Cost Analysis Division (CAD). Questions about SERRA should be directed to CAD at *hq-cad@mail.nasa.gov*. Sample schedule inputs and outputs for SERRA are provided in Figure K-3 along with a tabular output shown in Figure K-4.

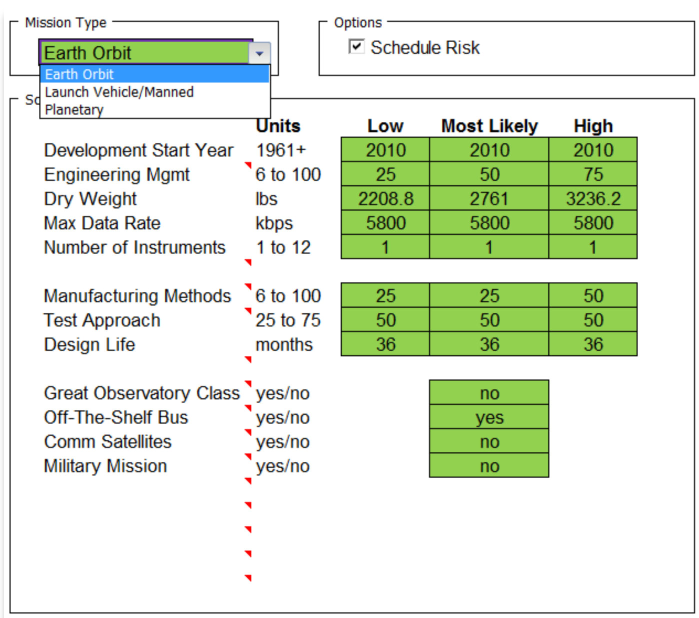


Figure K-3. SERRA Schedule Model Inputs

4 QuickCost 5.0, Joseph Hamaker, Ph.D., 2011.

5 *jhamaker@galorath.com*. For more information on QuickCost, see Appendix E.

6 SERRA User Guide, SAIC, August 2010. For more information about SERRA, see Appendix E.

Outputs of Lognormal:

	Design	Manuf	Total
Mean	16.8	32.1	48.9
Median	14.9	28.5	45.7
Mode	11.7	22.6	39.9
σ	8.8	16.5	18.7
5th	6.6	12.9	24.9
10th	7.9	15.3	28.5
20th	9.9	19.0	33.5
30th	11.5	22.1	37.7
40th	13.2	25.2	41.6
60th	16.9	32.3	50.2
70th	19.3	36.8	55.5
80th	22.6	42.9	62.4
90th	28.0	53.1	73.4
95th	33.5	63.4	84.0

Outputs of Normal:

	Design	Manuf	Total
Mean	16.8	32.1	48.9
Median	16.8	32.1	48.9
Mode	16.8	32.1	48.9
σ	8.8	16.5	18.7
5th	2.3	4.9	18.1
10th	5.5	10.9	24.9
20th	9.4	18.2	33.2
30th	12.2	23.4	39.1
40th	14.6	27.9	44.2
60th	19.1	36.3	53.7
70th	21.5	40.8	58.8
80th	24.3	46.0	64.7
90th	28.1	53.3	73.0
95th	31.3	59.3	79.8

Figure K-4. SERRA Schedule Model Tabular Outputs

K.4.5. Schedule Management and Relationship Tool (SMART)

The Schedule Management and Relationship Tool (SMART) combines analogy-based and parametric methods in a schedule estimating tool for unmanned spacecraft projects. The tool utilizes high-level technical and programmatic characteristics to determine a spacecraft's likely development schedule duration. It incorporates several previously developed third-party schedule estimating relationships (SERs) for comparison. SMART was developed by SpaceWorks Enterprises, Inc. (SEI) and is available via the NASA ONCE Model Portal at *www.oncedata.com*.

K.5. Schedule Data

Raw schedule data used to develop SERs can be found in various locations. The schedule data are spread across the Agency, and analysts can expect to expend some effort during data collection.

Fortunately, recent efforts to consolidate and organize the data have made this job somewhat easier. The Cost Analysis Data Requirement (CADRe) data and the One NASA Cost Engineering (ONCE) database are excellent data sources for collecting duration information, at *www.oncedata.com*. Examining prior research from the Aerospace Corporation as well as the Air Force Cost Analysis Agency (AFCAA) and the National Reconnaissance Office (NRO) can also provide the analyst with previously created schedule databases for SER development.

K.6. SER Research

In 2009 and 2010, NASA CAD commissioned MCR, LLC, to enhance and upgrade the database of satellite and payload schedules, focusing on the time required to move from one development milestone to the next. This work builds upon a previous database developed under a joint AFCAA/NRO task organized by the NRO Cost Analysis Improvement Group (CAIG). This research resulted in the creation of many individual SERs and a large database of schedule information for the Department of Defense (DOD), NASA, and NRO missions.

The resulting unclassified spacecraft database for satellite SER development contains 247 data records and is segregated by mission type. The resulting unclassified payload database contains 519 data records and is also segregated by mission type.[7] The data are further segregated by the various

[7] NRO Cost Group (NCG) Data Books—an ongoing collection from Government and industry, 1995 to present.

hardware vendors and identified by agency sponsor (e.g., DOD, NRO, or NASA). Parameters for mission design life (DL), end of life (EOL) date, and failure cause are included in the database to allow additional analysis of actual versus estimated plots that may suggest a relationship between the probability of premature failure and schedules that are less than the estimated schedules predicted by the SERs.

The research itself developed SERs for the time between spacecraft and instrument development milestones, including Authorization to Proceed (ATP), Preliminary Design Review (PDR), Critical Design Review (CDR), Integration and Test (I&T), Payload Delivery (DEL), First Launch Availability (FLA), and others as supported by the data. Figures K-5 and K-6 summarize the spacecraft SER and instrument SER types, respectively.

SER #	Duration	Dataset Used
Authority to Proceed (ATP) to First Launch Availability (FLA) SERs		
1	ATP-FLA	NASA only – All Spacecraft (SC)
2	ATP- FLA	NASA only – Planetary SC
3	ATP- FLA	NASA only – Non-Planetary SC
System Requirements Review (SRR) to FLA SERs		
4	SRR- FLA	NASA only – Planetary SC
5	SRR- FLA	NASA only – Non-Planetary SC
Beginning of System Test (BST) to FLA SERs		
6	BST- FLA	NASA only – Planetary SC
ATP to End of System Test (EST) SERs		
7	ATP-EST	NASA only – All SC
8	ATP-EST	NASA only – Non-Planetary SC
ATP to Ship Date (SD) SERs		
9	ATP- SD	NASA only – All SC
10	ATP- SD	NASA only – Non-Planetary SC

Figure K-5. NASA Spacecraft SER Types Developed by MCR

SER #	Duration	Dataset Used
1	ATP-DEL	Total Unclassified Database
2	CDR–DEL	Total Unclassified Database

Figure K-6. Instrument SER Types Developed by MCR

The SERs were developed using three statistical methods: (1) Ordinary Least Squares (OLS), (2) Minimum Percentage Error–Zero Percentage Bias (MPE-ZPB or ZMPE), and (3) Errors in Variables (EIV) regression.

The resulting SERs' goodness-of-fit statistics that were developed under this task, in general, are poorer fit statistics (as expressed by error residuals, degrees of freedom, and R^2) than would be found in CERs. The criteria for selecting recommended SERs were thus relaxed for this research to include SERs with a standard error of 40 percent and R^2 at or above 50 percent.

The two primary SER drivers that were collected and used in SER development were dry mass and beginning of life (BOL) power. The primary driver of schedule is the size of the program as measured by complexity. Both dry mass and BOL power are often used as proxies for measuring this complexity. In general, the higher a spacecraft mass and the more power it requires, the more complex it is. Another driver that is often seen in SERs is DL. Longer DL often necessitates more testing to ensure that the spacecraft lasts as long as advertised. In order to consider the "newness" of the spacecraft, an indicator variable for block change/new design was also collected in the research. This allows the analyst to distinguish from follow-on spacecraft and spacecraft undergoing major changes that could result in significant design challenges. Two additional metrics were collected to capture the amount of diversity present in the spacecraft development process: the number of mission types and the number of distinct payloads.

Quality metrics are calculated for each SER to provide the user with an understanding of the likely accuracy of estimates based on that SER. These quality metrics depend on the values of the drivers in the database alone and not on any probabilistic assessment of the expected growth of the drivers of the particular SER involved. Therefore, during a typical risk analysis, the user should consider probable growth in the drivers, which can help account for estimating the a posteriori value of schedule duration using a priori values for schedule drivers.

Figure K-7 shows an example SER for ATP to FLA for a planetary spacecraft using ZMPE.

The complete research report, results, and Excel database are available from CAD upon request.

Applicability: All Unmanned NASA Planetary Space Vehicles

Method: Estimation of Time from ATP to First Launch (mos) vs. Dry Mass (lbs) and IMINT / Remote Sensor

Estimating Relationship: **Y = 5 + 0.581 * X1 ^ (0.785) * (0.286) ^D1**

Y = Time from ATP to First Launch (mos)

X1 = Dry Mass (lbs)

D1 = IMINT / Remote Sensor

REGRESSION METHOD: Constrained Optimization of SER coefficients:
Minimized standard error with zero bias constraint

SIGNIFICANCE TESTS:

SER Form Y=a+b(X1)^c d^(D1)

Coef	Value	Significance	
a	5.24	-3.41E-02	significant
b	0.58	-1.44E-02	significant
c	0.79	5.93E-01	significant
d	0.29	5.91E-01	significant

SER STATISTICS:

% Standard Error (Multiplicative Error)	34.7%	**# Observations**	30
Pearson's Correlation Squared (R^2)	54.7%	**# Coefficients**	4
Bias %	0.0%	**Deg. Of Freedom**	26

FIT RESULTS: Reasonable fit to data. Reasonable standard error. Zero Bias.

Figure K-7. SER for ATP to FLA of Planetary Spacecraft Using ZMPE

K.7. SER Example Using SERRA

The following example shows how an analyst can use programmatic data and a SER to estimate schedule duration. In this example, the analyst is tasked to perform a parametric schedule estimate. The analyst has reviewed preliminary program summaries and selected the planetary spacecraft mission type from SERRA since these most closely match the current program.

The analyst collects the following technical and programmatic data from the Project Office[8,9]:

- Mission Type = planetary spacecraft
- Schedule Start (StartYr) = 2011 (schedule start Base Year is 1960)
- Engineering Management (StreamEM) = 25 (few design changes, Skunk-Works approach)
- Satellite Dry Weight (DryWt) = 1,800 pounds
- Maximum Data Rate (MaxData) = 256 kilobytes per second

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[8] The model variable names are provided in parentheses next to the input parameter name.

[9] Both engineering management and funding availability are based on scales of 0 to 100.

- Number of Instruments (NumInst) = 8
- Funding Availability (FundAvail) = 50 (some infrequent delays possible)
- Mission Design Life (DesignLife) = 24 months from launch to end of mission (includes transit time)
- Power Source: Radioisotope Thermoelectric Generator (RTG); (1 = no RTG, 0 = RTG)

The Engineering Management input describes the level of design changes, experience of the design team, and environment of the design effort, as follows:

- 0—Minimum design changes with design team, making maximum use of highly efficient Skunk Works approach with Integrated Product Teams (IPTs), rapid prototyping, design to cost, etc.
- 25—Few design changes using a highly efficient Skunk Works approach with IPTs, rapid prototyping, design to cost, etc.
- 50—Moderate design changes with an application of advanced design methods, including concurrent engineering, tailored specifications, minimum reporting, etc.
- 75—Dedicated design team dependent on some technology advances that encounter significant requirements changes
- 100—Distributed design team dependent upon major technology advances and experiencing frequent major requirements changes

The Funding Availability input reflects the appropriate anticipated funding availability. Choices for Funding Availability include the following:

- 25—Funding is assured; no delays
- 50—Some infrequent delays possible
- 75—Funding is constrained; delays likely

The appropriate equations in SERRA for estimating planetary mission schedule phases are as follows:

Schedule Duration (ATP to CDR)

$$Start\_CDR\_Dur = 0.759 FundAvail^{0.420} StartYr^{0.337} DesignLife^{0.229} StreamEM^{-0.393} RTG^{0.599}$$

Schedule Duration (CDR to Delivery)

$$CDR\_Delivery\_Dur = 5.279 TechnicalRating^{0.065} StreamEM^{-0.824} StartYr^{0.613} RTG^{0.376}$$

Where $TechnicalRating = (DryWt - 100)/4000 + (NumInst - 1)/12 + MaxData/256$

It is important to realize for log-transformed regression that a “no” input translates to a value of 1.0 and a “yes” input translates to a value of 2.71828. StreamEM is a yes/no input based on a streamlined engineering management approach (yes, in this case). Also for these SERs, the input for the year of schedule start is normalized by subtracting 1960 from the year of start. The RTG input is yes/no as well, and since this spacecraft is not powered by an RTG, the value input in the SER equation is 1, regardless of what other power source might be used.

The SER equations with the appropriate programmatic inputs collected above are:

Schedule Duration (ATP to CDR)

$$Start\_CDR\_Dur = 0.759(50)^{0.420}(2011-1960)^{0.337}(24)^{0.229}(2.71828)^{-0.393}(1)^{0.599} = 20.64$$

Schedule Duration (CDR to Delivery)

$$TechnicalRating = (1800 - 100)/4000 + (8-1)/12 + 256/256 = 2.008$$

$$CDR\_Delivery\_Dur = 5.279(2.008)^{0.065}(2.71828)^{-0.824}(2011-1960)^{0.613}(1)^{0.376} = 26.98$$

Thus, the estimate development phase **(ATP to CDR) duration is 21 months**, and the estimated manufacturing phase **(CDR to delivery) duration is 27 months**.