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MISSION OPTIONS SCOPING TOOL FOR MARS ORBITERS: MASS-COST-CALCULATOR (MC^2)

Erick J. Sturm II, Marie-Jose Deutsch[*], Corey Harmon[*], Roy Nakagawa[†], Robert Kinsey[‡], Nino Lopez[*], Paul Kudrle[*], Alex Evans[*]
[*]Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099
[†]Alliance Spacesystems, LLC
1250 Lincoln Avenue, Suite 100, Pasadena, CA 91103
[‡]The Aerospace Corporation
2350 E. El Segundo Boulevard, El Segundo, CA 90245-4691
e-mail: Erick.J.Sturm@jpl.nasa.gov

ABSTRACT

Prior to developing the details of an advanced mission study, the mission architecture trade space is typically explored to assess the scope of feasible options. This paper describes the main features of an Excel-based tool, called the Mass-Cost-Calculator (MC^2), which is used to perform rapid, high-level mass and cost options analyses of Mars orbiter missions. MC^2 consists of a combination of databases, analytical solutions, and parametric relationships to enable quick evaluation of new mission concepts and comparison of multiple architecture options. The tool's outputs provide program management and planning teams with answers to "what if" queries, as well as an understanding of the driving mission elements, during the pre-project planning phase. These outputs have been validated against the outputs generated by the Advanced Projects Design Team (Team X) at NASA's Jet Propulsion Laboratory (JPL). The architecture of the tool allows for future expansion to other orbiters beyond Mars, and to non-orbiter missions, such as those involving fly-by spacecraft, probes, landers, rovers, or other mission elements.

INTRODUCTION

Processes currently used to assist a principal investigator (PI) or advanced mission study lead scope a future space mission involve the support from a concurrent study team, like Team X and a proposal team at JPL, or alternatively require the use of modeling capabilities. Scoping entails exploring the mass, cost and payload trade space to optimize science return. Software tools typically call for a large number of engineering parameters, which are not always known at this early stage in the mission concept. As a result many advanced studies remain ill-defined even as support from Team X is sought, frequently resulting in expensive, non-optimum point solutions.

An idea emerged among the members of the Mars Program Advanced Studies Office to use the large set of advanced studies that JPL has done over the past six years (more than 90 studies for Mars alone) and develop a capability to scope missions by analogy to existing missions and advanced studies held in the Team X database. These missions and studies had been developed with the help of experienced teams assembled from within the technical areas of JPL at considerable expense.

Capturing the explicit knowledge but more importantly the tacit knowledge embedded in these missions and studies would have the added benefit of making the derived mission options more realistic from a cost and risk point of view.[1,2,3] Less feasible options could be flagged early during the initial scoping process. The second advantage is that a software tool using analogy could significantly minimize the number of input parameters a PI would have to know a priori. Instead rules of thumb and parameter choices derived from missions having carried similar types of instruments would make choices intuitive. Tens of options could be generated with relative ease, within hours, enabling the best solution to be brought forward for further development within a concurrent design team. The result of this work allows the PI or the Mars Program Office to find quick and accurate (to within 10 % of existing missions and studies) solutions to "what-if" questions.

OVERVIEW

Scope

The initial release of the MC^2 tool is limited to the study of Mars orbiter missions. The tool is able to estimate the mass and cost of a wide range of Mars orbiters by accounting for a variety of mission design parameters such as launch dates, types of Earth-Mars trajectories, types of Mars orbit insertion maneuvers, types of propulsion systems, changes in orbital altitudes, whether or not aerobraking is used, etc. It also factors in a number of cost drivers such as the phase durations, number and complexity of instruments, downlink data rate, science data volume, etc. The tool enables the user to make intelligent choices for the individual instruments and spacecraft subsystems from a database of previous Team X studies and calculates the total wet mass and project costs with appropriate contingency and reserve values.

Methodology

MC^2 is designed with the idea of maximizing speed and fidelity while minimizing complexity and cost. These factors are at odds with each other. Typically high fidelity tools are complex and require many user inputs that are not available at the early concept stage of a mission, while low complexity tools produce results with large margins of error that are usually only used to establish relative trends and not for their absolute values. Estimates with high fidelity and low complexity are possible for masses calculated from first principle equations requiring few inputs that are known early on in the design process, as well as for subsystems which have a strong correlation to such a mass allowing for a rule-of-thumb to be derived.

Whenever possible, first principles and rules-of-thumb were used to produce MC^2 estimates. The propellant mass and propulsion system mass are examples of these. In MC^2, the propellant mass is calculated from the rocket equation, the inputs of which are known – or at least accurately estimated – very early in the design process. Thus, MC^2 calculates the wet mass from the dry mass based on first principles. The propulsion subsystem mass is highly dependent on the propellant mass, as can be seen in Figure 1.

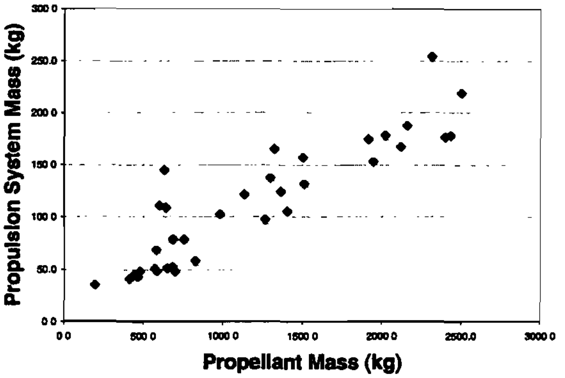


Figure 1: Correlation between Propulsion System and Propellant Masses

From this data, a rule-of-thumb was developed and implemented into MC^2 for estimating the propulsion subsystem mass from the propellant mass.

The data from the existing studies and missions, however, did not always lend themselves to easy derivations of rules-of-thumb as the scatter plot reveals in Figure 2. This is believed to be the result of JPL developing non-repetitive, one-of-a-kind missions. For these cases, the idea emerged of using a relatively small set of "reference missions" to direct the user toward a class of missions roughly appropriate for the study. If the user's requirements are not adequately met with the default parameter value of the reference mission, then the database may be used to find a better value for each such parameter. If a better value does not exist in the database, the user may override the suggested parameter value. Any new study, as long as it does not diverge radically from previous missions, could be adequately constructed with this method. Test results show that the output values obtained from MC^2 do not diverge more than 10% from the studies developed by Team X.

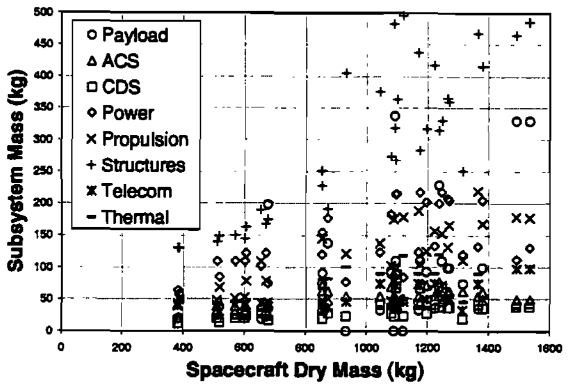


Figure 2: Scatter-Plot of Subsystem Mass vs. Spacecraft Dry Mass

The "by-analogy" method of creating the inputs required by MC^2 is used for the payload and all the spacecraft subsystems except for propulsion, as discussed above, and structures, which is discussed later in this paper. This method allows for the generation of results early in the design process with relatively low margins of error because the user does not have to guess the values of large numbers of inputs.

The "by-analogy" methodology is inherently limited by the requirement that the databases used, in conjunction with the tool itself, be kept up-to-date. The accuracy of the data in these databases limits the accuracy of the tool. As such, as Team X discovers errors in its design tools, and updates old studies, so must the databases in MC^2 be updated. An additional limitation of the tool is that any study developed using it cannot diverge too radically from the previous missions and studies in the database. If a mission uses a staged spacecraft design for instance, the tool will not be useful, as no similar mission exists in the database.

MC^2 was developed by "prototyping a little", then "implementing a little" and "testing a little", while the next feature was being prototyped. Key user validation was undertaken part way through the development cycle, allowing for incremental improvement before final delivery.

ARCHITECTURE

MC^2 is a Microsoft Excel workbook that uses databases, parametric models, Visual Basic for Applications (VBA), and user inputs to generate mass and cost estimates for a Mars orbiter mission. The high-level tool architecture is shown in Figure 3. The boxes are user inputs, the cylinders are databases, the parallelograms are data populated from the databases, the ovals are calculations, and the octagons are outputs.

The main theme in the user interface with the tool is the ability for the user to use databases to populate tool inputs with reference values from a similar Team X study. The user then has the ability to use these values or to adjust them as necessary for the particular mission being studied. The fact that the user can start from a reference mission and modify only those inputs that are of particular importance to the current study means that the user does not have to waste time entering all the inputs from scratch. Thus, MC^2 is able to have the fidelity of other more complex tools, but the speed and ease of use of a spreadsheet.

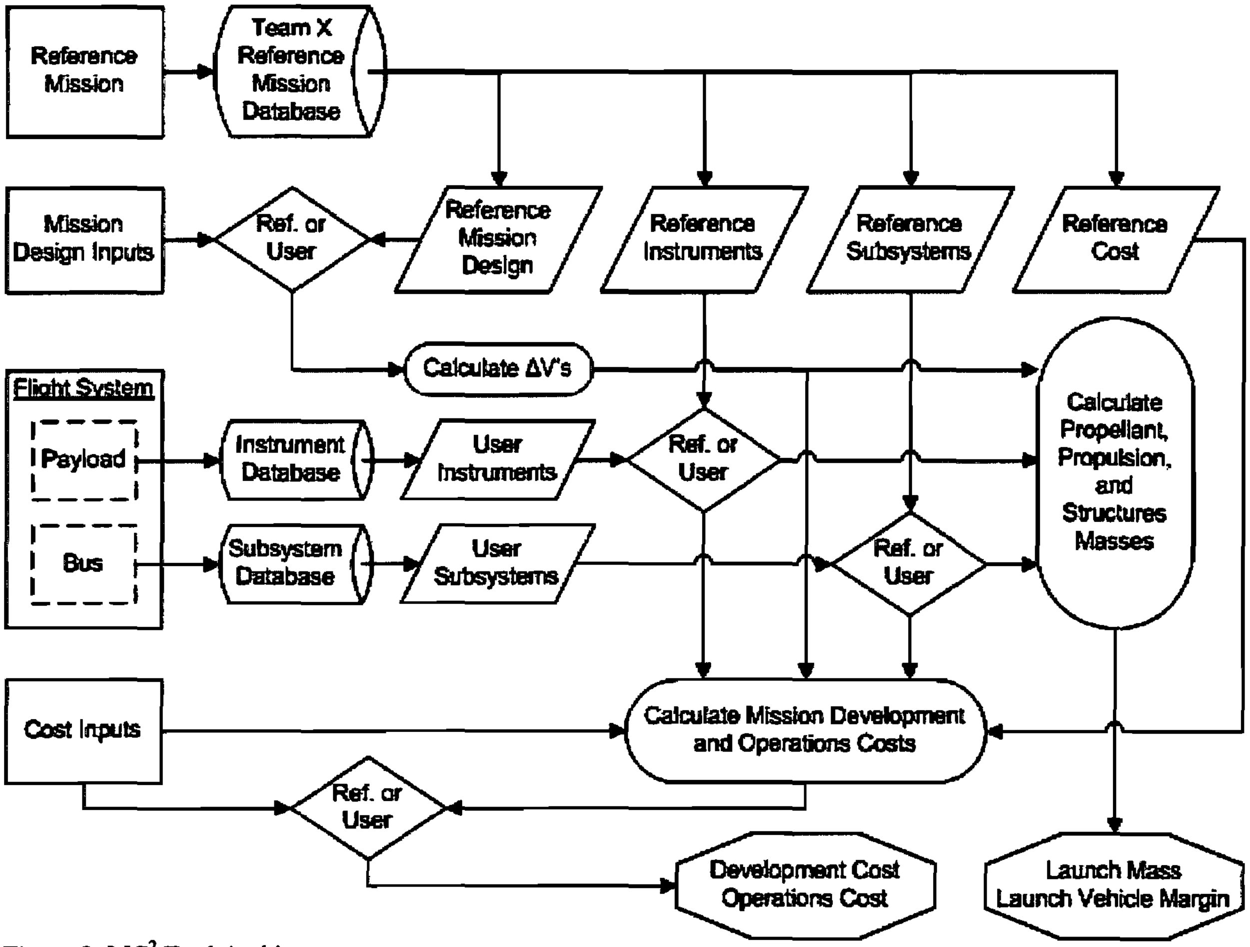


Figure 3: MC^2 Tool Architecture

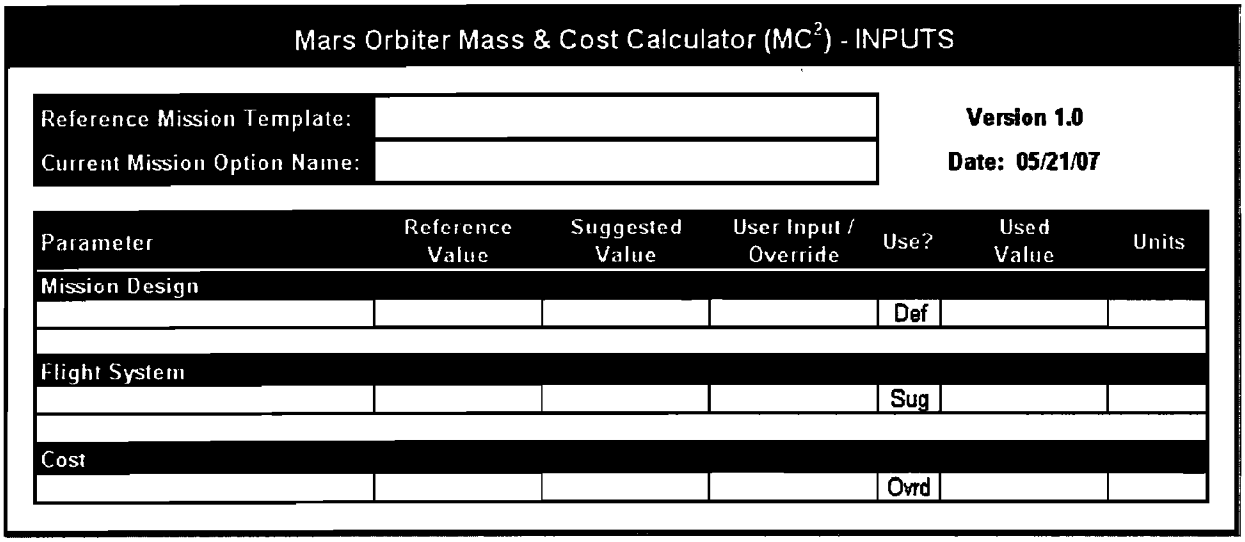
Because MC^2 is dependent on various databases to compile mass and cost data, some of these databases must be kept current or else the tool could become outdated or even obsolete. For example, the tool relies on the launch vehicle performance data from NASA KSC which is periodically updated to reflect changes in performance due to launch vehicle upgrades. Another example is the science instruments database which needs to be updated periodically to keep pace with often times radical advancements in measurement technology. In addition, mass and cost data from new reference missions should be added to the database each time a new Team X study is performed or actual data become available from completed flight missions. Mass and cost models and parametric relationships may also require periodic updating.

The remainder of this section will focus on the high-level details of the inputs, databases, calculations, and outputs of MC^2.

Inputs

All inputs to MC^2 are entered using a single consolidated user input sheet shown in part in Figure 4. Each of the inputs can be populated instantly by selecting one of the reference missions contained in the tool's database. The selection is based on what the user would like to use as a starting point or a baseline for comparison of subsequent changes made to the input parameters. In other words, the mission chosen is most similar to those that the user expects to construct with the tool.

A key feature of the input sheet is that it has four distinct columns of values for each input parameter. They are: Reference Value, Suggested Value, User Input/Override, and Used Value. Also, its rows are divided into three main input sections. These sections are Mission Design, Flight System, and Cost.



Mars Orbiter Mass & Cost Calculator (MC^2) - INPUTS

Reference Mission Template:

Current Mission Option Name:

Version 1.0

Date: 05/21/07

Parameter	Reference Value	Suggested Value	User Input / Override	Use?	Used Value	Units
Mission Design						
				Def		
Flight System						
				Sug		
Cost						
				Ovrd		

Figure 4: Format of the MC2 Inputs Worksheet

Input Worksheet Columns

The Reference Value column corresponds to the reference values associated with the selected reference mission; when the user selects the reference mission of choice, the tool automatically populates each cell in the column with appropriate values from the database.

The Suggested Value column corresponds to values that the tool is designed to generate as the user runs its various built-in features; science instruments and spacecraft subsystem suggested values are generated when the user selects a particular design from a database of Mars science instruments and orbiting spacecrafts.

The User Input/Override column corresponds to values which the user inputs directly as potential overrides to the reference or the suggested values; reasons for entering the user's own values include, but are not limited to the user obtained his/her own value from some external source or calculation, or the user wants to see the effects on the outputs of varying a specific input parameter by a given amount.

The Used Value column corresponds to values that the user has specifically chosen to use for all calculations performed by the tool; the values can be those from either the reference, suggested, or override columns.

Input Worksheet Rows

The rows of the input worksheet hold the individual input parameters. These parameters are then split into three input categories: Mission Design, Flight System, and Cost.

The Mission Design section is where the user gives all the inputs that affect the ΔV budget of the spacecraft. The main inputs in this category are Launch Year, Mars Orbit Insertion Method (propulsive or aerocapture), and the Apoapse and Periapse of each Orbit. The user can also specify if aerobraking should be used to change between orbits when possible. The tool then uses these inputs to calculate a launch C3, arrival VHP, and ΔV for orbit changes. All of these can be overridden by the user in the Override column.

The Flight System section is where the user specifies the orbiter payload and the subsystems to support that payload. Both the payload and bus sub-sections are pre-populated with the reference mission's data. The user can then select instruments and subsystems from the built in database or just directly enter in the mass and cost of a custom instrument or subsystem in the Override column. This is true for all the subsystems except propulsion and structures, which are calculated by the tool. This will be discussed in more detail in the next subsection of this paper. The propulsion system type and propellant specific impulses are also entered in this section.

The Cost inputs section has inputs for mission schedule and operations. It also has all the work breakdown structure line items that are calculated by the tool, which allows the user to adjust any of the estimates in the Override column.

Databases and Models

A key feature of the MC^2 tool lies in its databases, which contain a wealth of mass and cost data from over 500 mission concept studies performed by Team X over the last five years. The current version of the tool contains data from 49 Mars orbiter studies. Since the mission studies range from small, inexpensive technology demonstrators to large, flagship missions, the user has a wide range of choices in payload and spacecraft subsystem designs to literally piece together a new design very rapidly. The tool's other key feature is its capability to calculate the mass of propellant required for the mission under study using a generic Mars orbiter mission architecture model generated by MassTracker[4] and populated based on all the various mission design, payload, and spacecraft subsystem information that the user selects as input. Lastly, the tool has the capability to calculate the cost of the mission under study using a combination of different cost estimating methods. These features enable the user to vary the inputs that define a particular option for a mission and quickly derive estimates of both the total mass and cost for comparative purposes without having to run a full concurrent design session.

Team X Reference Mission Database

Subsystem mass and cost data from close to 50 Team X studies of Mars orbiter missions have been compiled to form a spacecraft subsystems database that resides within the MC^2 tool. In addition to the mass and cost of each of the subsystems that make up the spacecraft bus on each of the nearly 50 Mars orbiter concepts, a summary of the key characteristics of the subsystems, such as power, dimensions, key performance specifications, etc. were also added as comment boxes to aid the user in its selection on the user input sheet. A placeholder also exists to capture major component mass and power specifications that make up the subsystems for possible future expansion of the database since Team X studies typically include a detailed MEL and PEL as part of their outputs.

Instruments Mass and Cost Databases

Mass and key characteristics data for over 60 instruments, which could be manifested on Mars orbiter missions, from previous Team X studies, and other sources, have been compiled to form a science instruments database that resides within the MC^2 tool. In addition to the mass, a summary of the key characteristics of the science instruments, such as power, dimensions, resolution/sensitivity, pointing requirements, data rate and data volume, etc., were also added as comment boxes to aid the user in its selection on the user input sheet.

The MC^2 tool relies on the NASA Instruments Cost Model (NICM) to generate cost estimates for a majority of the instruments contained in the instruments database. NICM is capable of deriving cost estimates for science instruments based either on component assemblies, parametric analysis, or analogous instruments. NICM has its own instruments database and some of the cost data were extracted directly from this database, but the MC^2 tool also relies on the parametric relationships based on the mass of the instruments. Since NICM is currently not integrated with the MC^2 tool, the costs of the instruments were generated separately by NICM and entered directly into the MC^2 instruments database. NICM has been fully validated and will be used by not only Team X at JPL, but also by NASA Headquarters.

Interplanetary Trajectory Selector

The Interplanetary Trajectory Selector uses the Launch Year, Trajectory Type, and Optimization Criteria to select an Earth-Mars heliocentric trajectory from a look-up table. The look-up table is populated with data from the "Mars Mission Opportunity Design Data Handbook"[5]. Technically, each of the above three inputs to the model is optional. If any of the inputs is missing the model will simply average the values of all the trajectories in its look-up table that satisfy the provided inputs. The launch year can be any year from 2011 to 2028. The trajectory can be types I, II, III, or IV. The optimization criteria can be either C3 or VHP. The model outputs are C3, DLA, V_∞, Launch Date, Arrival Date, and Cruise Duration all averaged for a 20 day launch period.

ΔV Calculator

The ΔV Calculator translates the inputted apoapses and periapses of the spacecraft's orbits into ΔV requirements. The model assumes a 2-body system and produces ideal instantaneous ΔV's for all cases except the orbit insertion ΔV which has 5% gravity losses added to it. In the case where the user has specified that aerobraking may be used when possible, the model will check to see if aerobraking is possible between two consecutive orbits. If aerobraking is possible, then the tool estimates the required ΔV to be that to lower periapse to an altitude of 75km and then raise it to the final orbit's periapse altitude.

MassTracker Architecture Model

MassTracker was used to generate a generic Mars orbiter architecture model. The model includes trans-Mars trajectory correction maneuvers, an orbit insertion event, and placeholders for ten different orbit change maneuvers. The method of using MassTracker to generate a generic architecture model is similar to that used by Balint et al. when estimating the amount of landed mass different launch vehicles could provide on the surface of Mars[6]. However, this model, instead of relying on gear ratios, is populated with the trajectory data from the Interplanetary Trajectory Selector and the ΔV data from the ΔV Calculator. It combines this data with the payload and subsystem masses calculated by the user. It then iteratively solves for the required propellant mass, propulsion subsystem mass, structures mass, and launch mass.

Propulsion and Structures Mass Algorithms

The propulsion and structures masses are the only subsystem masses that can be parametrically calculated by the tool, meaning they do not require population from a database nor input from the user. The reason for this is that these two subsystem masses are highly dependent on propellant, and pretty much any change the user makes to a reference mission will result in a propellant mass change. However, it is still possible for the user to override these subsystem mass estimates on the inputs worksheet.

The propulsion subsystem mass is estimated as a percentage of the spacecraft dry mass plus a percentage of the spacecraft propellant mass. The percentages were determined by a curve fit to the Team X propulsion subsystem masses in the database. The structures mass is estimated using the same parametric model used in Team X. The model takes different percentages of the payload mass, subsystem masses, and propellant mass to calculate the required structures mass.

Launch Vehicle Selector

The Launch Vehicle Selector is populated with launch vehicle capabilities from the Kennedy Space Center website. It is also populated with the launch vehicle cost estimates used by Team X. The model takes the C3 and DLA values from the Trajectory Selector and looks-up the launch vehicle capabilities of the Atlas, Delta, and Taurus families for the specified trajectory, de-rating them for the given DLA based on Figure 5. It then compares these values to the spacecraft launch mass and chooses the lowest cost launch vehicle that has a capability greater than the launch mass. The model's outputs are launch vehicle, its capability, its cost, and the launch vehicle margin.

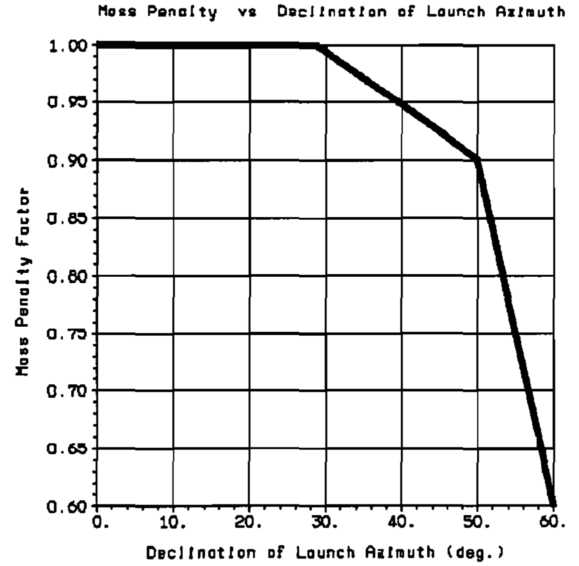


Figure 5: Launch Vehicle Capability Penalty Factor vs. Declination of the Launch Azimuth

Science Cost Model

The science team cost estimate is based on a simplified version of the Team X cost model. Its inputs include the number of instruments, mission phase duration, the operational complexity of each instrument (i.e., "simple," "moderate," "complex"), and whether or not they are university built.

Mission Operations System/Ground Data System & Mission Design/Navigation Costs Model

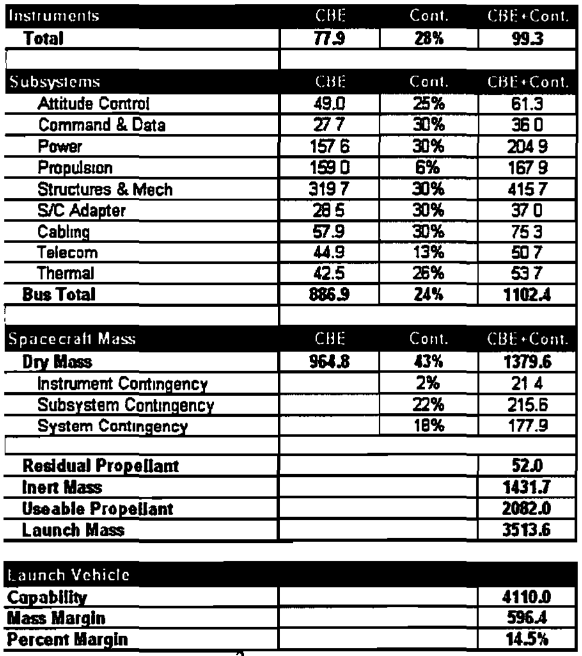
This model determines cost based on the overall mission complexity. Weighted factors are applied to the inputs, which are then summed into a complexity score. The complexity score determines what level of costs should be applied to the mission durations. The model assumes JPL manages the mission along with the following assumptions. Development and operations delivery schedules for GDS are every 6 and 18 months, respectively. There is no deferred development or foreign contractor building the spacecraft. Also it assumes a direct-to-Earth link and does not handle radio science processing analysis. The main inputs to the model are the number and complexity of instruments and spacecraft, the development and operations schedules, and the science downlink rate and daily data volume. This model provides cost for the functions required in preparation for launch and for flight operations: spacecraft team, mission control team, instrument operations, data management, science planning, ground data system, system administration, as well as mission design and navigation.

Management and Systems Engineering Costs

The management and systems engineering costs are estimated as percentages of various sums of the work breakdown structure line items. The percentages used are the same as those used in Team X.

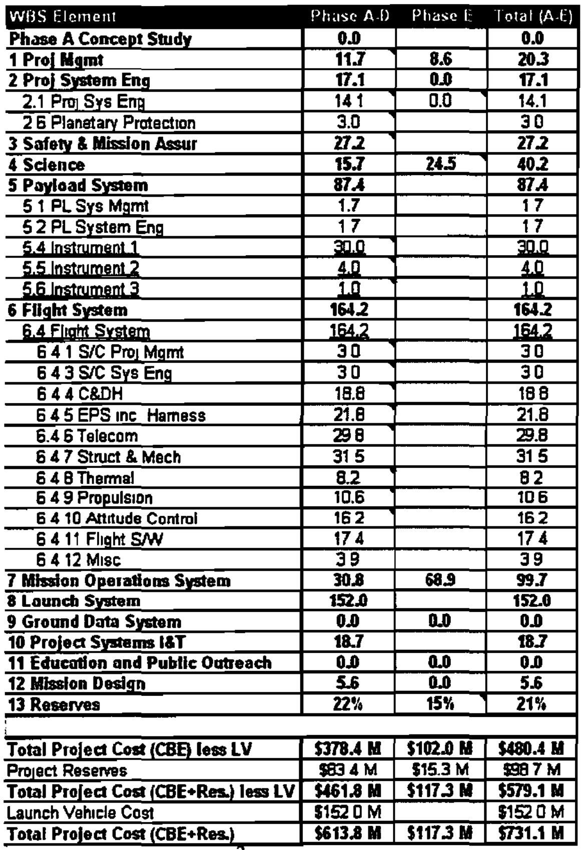
Outputs

As the name implies, the main outputs of MC^2 are mass and cost. The masses calculated by the tool are propellant mass, propulsion mass, structures mass, and launch mass. These are then used with the Launch Vehicle Selector to provide a launch vehicle mass margin. A typical mass output table is shown in Figure 6. MC^2 also calculates development and operations costs, each line item of which is shown in the work breakdown structure in Figure 7.



Instruments	CBE	Cont.	CBE+Cont.
Total	**77.9**	**28%**	**99.3**
Subsystems	CBE	Cont.	CBE+Cont.
Attitude Control	49.0	25%	61.3
Command & Data	27 7	30%	36 0
Power	157 6	30%	204 9
Propulsion	159 0	6%	167 9
Structures & Mech	319 7	30%	415 7
S/C Adapter	28 5	30%	37 0
Cabling	57.9	30%	75 3
Telecom	44.9	13%	50 7
Thermal	42.5	26%	53 7
Bus Total	**886.9**	**24%**	**1102.4**
Spacecraft Mass	CBE	Cont.	CBE+Cont.
Dry Mass	**964.8**	**43%**	**1379.6**
Instrument Contingency		2%	21 4
Subsystem Contingency		22%	215.6
System Contingency		18%	177.9
Residual Propellant			**52.0**
Inert Mass			**1431.7**
Useable Propellant			**2082.0**
Launch Mass			**3513.6**
Launch Vehicle			
Capability			**4110.0**
Mass Margin			**596.4**
Percent Margin			**14.5%**

Figure 6: Typical MC^2 Mass Output



WBS Element	Phase A-D	Phase E	Total (A-E)
Phase A Concept Study	**0.0**		**0.0**
1 Proj Mgmt	**11.7**	**8.6**	**20.3**
2 Proj System Eng	**17.1**	**0.0**	**17.1**
2.1 Proj Sys Eng	14 1	0.0	14.1
2 6 Planetary Protection	3.0		3 0
3 Safety & Mission Assur	**27.2**		**27.2**
4 Science	**15.7**	**24.5**	**40.2**
5 Payload System	**87.4**		**87.4**
5 1 PL Sys Mgmt	1.7		1 7
5 2 PL System Eng	1 7		1 7
5.4 Instrument 1	30.0		30.0
5.5 Instrument 2	4.0		4.0
5.6 Instrument 3	1.0		1.0
6 Flight System	**164.2**		**164.2**
6.4 Flight System	164.2		164.2
6 4 1 S/C Proj Mgmt	3 0		3 0
6 4 3 S/C Sys Eng	3 0		3 0
6 4 4 C&DH	18.8		18 8
6 4 5 EPS inc Harness	21.8		21.8
6.4 6 Telecom	29 8		29.8
6 4 7 Struct & Mech	31 5		31 5
6 4 8 Thermal	8.2		8 2
6 4 9 Propulsion	10.6		10 6
6 4 10 Attitude Control	16 2		16 2
6 4 11 Flight S/W	17 4		17 4
6 4 12 Misc	3 9		3 9
7 Mission Operations System	**30.8**	**68.9**	**99.7**
8 Launch System	**152.0**		**152.0**
9 Ground Data System	**0.0**	**0.0**	**0.0**
10 Project Systems I&T	**18.7**		**18.7**
11 Education and Public Outreach	**0.0**	**0.0**	**0.0**
12 Mission Design	**5.6**	**0.0**	**5.6**
13 Reserves	**22%**	**15%**	**21%**
Total Project Cost (CBE) less LV	**$378.4 M**	**$102.0 M**	**$480.4 M**
Project Reserves	$83 4 M	$15.3 M	$98 7 M
Total Project Cost (CBE+Res.) less LV	**$461.8 M**	**$117.3 M**	**$579.1 M**
Launch Vehicle Cost	$152 0 M		$152 0 M
Total Project Cost (CBE+Res.)	**$613.8 M**	**$117.3 M**	**$731.1 M**

Figure 7: Typical MC^2 Cost Output

VALIDATION

Due to the MC^2 databases and parametric models being based on Team X data, the validation of the tool consisted of comparing its outputs to final design outputs generated by Team X. The goal was to validate the parameters calculated by the tool: orbital mechanics/delta-V, propulsion and structure subsystem dry mass and cost, propellant mass, and project level costs. Because the tool is currently designed for Mars orbiters only, the validation data set was limited to Team X Mars orbiter studies.

For each validation case, the Team X study parameters were entered into the tool and the appropriate payloads and subsystems chosen from the tool's database. The results of the calculated MC^2 parameters were compared with those from the Team X design; the validation results are shown in Table 1[7]. The desired performance of MC^2 is to be within ±10% of the Team X study outputs.

MC^2 Output	Average Error	Standard Deviation
Launch Mass	-10%	4%
Dev. Cost	-4%	8%
Ops. Cost	13%	40%

Table 1: MC^2 Validation Results Summary

The launch mass and development cost estimates generated by MC^2 fall within the desired performance. The operations cost is just outside the desired range, though it is believed to be mostly due to discrepancies in the science team cost estimate generated by both MC^2 and Team X.

The Science Cost Model incorporated into MC^2 does not account for individual operational durations of instruments over the mission lifetime. A particular validation case consisted of a multi-instrument payload, but the major science instrument was only operating for the first year of the five year science mission. MC^2 was not able to take this into account and thus overestimated the total science cost. Taking into consideration the operational lifetimes of each of the instruments would help improve the science team cost estimate without adding much complexity in the required tool inputs.

There is also an unexplained discrepancy in Phase E science costs for a particular validation case where the Team X Science Chair recorded the operations cost as $43M, but the Team X Cost Chair reported $25; the MC^2 tool estimated the cost at $48M. Since the Cost Chair is the official custodian of the final Team X costs, the lower cost was used in the validation. However, if it is assumed that the cost the Science Chair reported was correct, then the average operations cost error drops to 0% with a standard deviation of 33%. In this case, the performance of MC^2 would be as desired for all of its outputs.

APPLICATIONS

This section discusses how MC^2 has been used at the Jet Propulsion Laboratory (JPL) in order to provide a deeper understanding of the possible applications of the tool.

Advanced Projects Design Team: Team X

Team X is JPL's concurrent engineering design team. Part of Team X's charter is to evolve and enhance existing Pre-Phase A/Phase A design team study processes, procedures, tools, and products. As such, Team X uses MC^2 both before and after a study.

Before a Mars orbiter study, the customer can meet with Team X to discuss which options should be studied during the design sessions. At these meetings, MC^2 can be used to give predictions of the mass and cost for each of the options. These predictions can the be used to refine which options actually get studied by Team X by comparing them to the customers required launch vehicle capability or cost cap. In this way, the customer does not waste time or money studying options that have no chance of meeting the mission constraints.

After such a study, the MC^2 database can be updated with the designs for each of the options studied during the sessions. Then a customer can return to Team X and see the effects of small deltas to one of the previously studied options without having to go through another whole concurrent design session.

Mars Science Orbiter Project

The Mars Science Orbiter (MSO) Team used MC^2 to explore a large trade space of possible science payloads and to understand how those payloads impacted the overall spacecraft design. They started by loading a previous orbiter design that Team X had studied that had similar mission constraints and spacecraft parameters. From this design, the team was able to refine the spacecraft by either choosing a more appropriate subsystem from the tool's database or overriding a subsystem mass and cost with a small delta.

For example, the MSO telecom system need to be more robust than the reference mission, so a new telecom subsystem mass and cost was selected from the MC^2 mission database. Because the tool's database included detailed subsystem characteristics, a more appropriate telecom subsystem was easily selected. In the case of the C&DH subsystem, the new design only required slightly larger memory storage than the reference mission, so a delta in mass and cost was used as an override input.

With this approach the team developed tens of options in less than a month, which allowed them to quickly answer management "what if" questions. In particular, they discovered how small their spacecraft could be given their lightest payload, as well as the sensitivity of the spacecraft to each of the instruments in that payload. Based on the data generated from the team's use of MC^2, they were able to develop trends relating different mission characteristics, such as mass and cost, to offer management an easy way to predict other data points. Figure 8 shows an example of one such sensitivity.

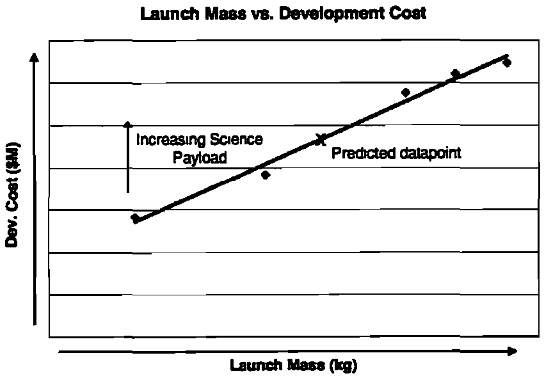


Figure 8: Sensitivity Example of Development Cost to Launch Mass

The MSO Team also used MC^2 to validate total launch mass estimates generated by the team's flight system engineer, identify the appropriate launch vehicle and its cost, and get an idea of which options were within the allocated budget for the project. They were also able to identify the different classes of science measurements that could be achieved with varying levels of budget increases.

FUTURE WORK

Additional capabilities could be added to size and different types of spacecraft, including in-situ elements (i.e., impactors, landers, rovers, airplanes, balloons, ascent vehicles, sample return capsules, etc.), such that assessments of Mars lander missions, and even a Mars sample return mission, could be performed. Further enhancements are envisioned to allow the tool to be used for rapid concept studies of missions to other solar system destinations such as Europa, Titan, Neptune, and even the Moon in support of current options being considered by NASA for lunar exploration.

A significant enhancement to the tool would be to add a front-end capability that would enable the user to enter key information about the science goals and measurement objectives which could then be translated into key instrument characteristics which in turn could be matched against corresponding data in the database and properly sized to meet the initial science requirements.

Along these same lines, linking each of the subsystems to the selected instruments and their requirements could enable the possibility of sizing the subsystems to meet the requirements with reduced user input. This would allow the user to focus less on propagating the effects of changes in payload, and more on how such changes affect the bottom-line outputs of mass and cost. Filtering the subsystems that the user can select from the database based on the instruments selected is a possible first step toward realizing this enhancement. The filtering would help the user select subsystems that could satisfy the payload requirements, thus helping to ensure that changes to payload are more accurately propagated to the final outputs.

CONCLUSION

MC^2 takes advantage of the many Mars orbiter mission concepts studied at JPL by the Mars Program Office in Team X. It uses a combination of first principles equations, rules-of-thumb, and "by-analogy" design to allow a user to quickly generate results shown to be within 10% of Team X estimates. MC^2 has been used by the Mars Science Orbiter team to explore their science mission trade space, as well as to learn the sensitivity of their spacecraft to its science instruments. MC^2 could be expanded to allow its users to analyze missions to other solar system bodies and non-orbiter missions. The efficiency and accuracy of MC^2 have made it a useful and powerful tool for aiding early mission concept design at JPL.

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