Design for X (DFX): Operations Characteristics Spacecraft Design Analysis Tool

Robert Sherwood, Steve Chien, Gregg Rabideau, Tobias Mann

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, M/S 525-3660
Pasadena, CA 91109-8099

Abstract

This paper describes a system to assist in evaluating operations characteristics of preliminary spacecraft designs. This system, called *Design for X* (DFX) requires: a set of operations goals (science and engineering goals and constraints), a model of the spacecraft, a model of spacecraft activities, and a set of scoring functions which evaluate the utility of different operations activities (e.g., science value). DFX uses this modeling information and artificial intelligence based planning and scheduling techniques to produce a high level activity plan that is then scored using the provided functions. This process automates the evaluation of spacecraft designs which has several benefits: improved science return due to optimized sciencecraft, improved spacecraft operability due to more accurate margins and interactions analysis, decreased project (e.g., budget, schedule) risk from using rapid prototyping and analysis of designs. In addition, such a tool could assist in performing more methodical trades analyses and the tool could be used for impartial analyses of science Announcements of Opportunity (AO)'s.

1. Introduction

Spacecraft design is a challenging task that is both knowledge and labor intensive. Spacecraft and mission designers must balance numerous competing constraints on mass, power, cost, volume, and other systems level interactions. In addition, many of the desired attributes of the end spacecraft cannot be directly evaluated as spacecraft parameters. For example, enhancing the science return is a desired goal. However, it is often difficult to evaluate the quantitative influence direct design parameters such as memory, or pointing speed would have on science return. Another example, ease of operation is a desired characteristic of a spacecraft. While many specific design parameters would make a spacecraft easier to operate (more power, more memory, less thermal constraints, etc.), knowing the exact impact of modifications on operability is more difficult. For example, which resources are closest to their margins during nominal science scenarios? Which resource usages are most sensitive to changes in the estimated slew times? How does downlink rate affect the memory margins? The Design for X (DFX) tool is intended to assist in answering these questions.

The DFX system is targeted at providing a "what-if?" capability for evaluating spacecraft designs. The intended method of usage for the DFX tool is shown below in Figure 1. The DFX system requires as input:

- A candidate spacecraft design (and operations constraints, models, etc.)
- A set of engineering and science objectives
- A set of scoring functions to assess how well a sequence achieves the objectives

The DFX inputs are created using the modeling language of the Automated Planning/Scheduling Environment (ASPEN). ASPEN provides a user-friendly modeling syntax that defines the spacecraft in terms of activities, resources, states, and constraints. Once the spacecraft is fully specified, ASPEN uses its planning and scheduling engine to generate an operations sequence of events and scores the sequence in terms of science, operability, etc. The scoring criteria are completely defined by the user within the model. The result is that the design team gets quantitative feedback on how well the design achieves science objectives and meets operability constraints (such as meeting power margins, etc.). This type of tool is targeted at enabling design teams to rapidly and impartially evaluate large numbers of spacecraft designs with little effort, thus allowing improved analysis of design tradeoffs to enhance science and operations concerns for future missions. The DFX tool has been tailored to maximize the automation of the optimization process and minimize the amount of customization required by the user. Other work in using planning

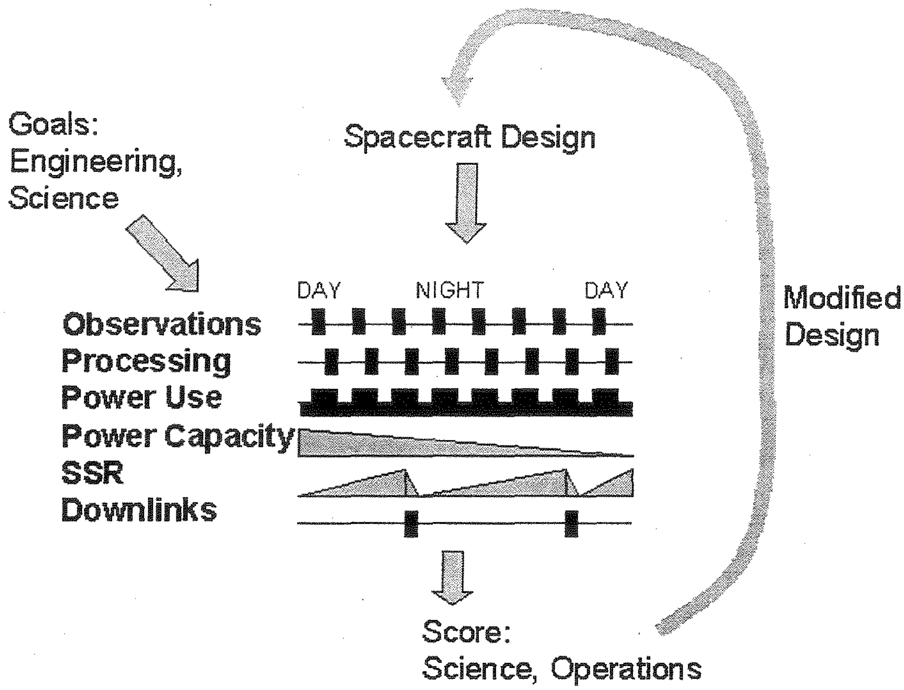


Figure 1: Intended Usage of DFX Tool

technology to evaluate mission requirements and mission designs includes [Ghallab, 1997].

The remainder of this paper is organized as follows. First, we briefly describe the basic planning and scheduling capability that we presume. We only outline this material because it has been covered in detail elsewhere. Then we describe a detailed application of the DFX concept to evaluation of competing designs for the Pluto Express Pre-project (now part of the Fire and Ice Program at the Jet Propulsion Laboratory). Next, we describe plans for the DFX project and conclusions.

2. Automated Planning and Scheduling

At the heart of DFX is an automated planning and scheduling capability. Planning is the selection and sequencing of activities such that they achieve one or more goals and satisfy a set of domain constraints. Scheduling selects among alternative plans and assigns resources and times for each activity so that the assignments obey the temporal restrictions between activities and the capacity limitations of a set of shared resources. In addition, scheduling is an optimization task in which metrics such as tardiness and make-span are minimized. Scheduling is a classical combinatorial problem that has long been studied by researchers in operations research.

Our DFX concept is built upon the ASPEN planning/scheduling system [Fukunaga et al. 1997]. In order to enable the rapid development of automated scheduling systems for NASA applications, we have developed ASPEN, a reusable, configurable, generic planning/scheduling application framework. ASPEN is an object-oriented system (implemented in C++) that provides a reusable set of software components that implement the elements commonly found in complex planning/scheduling systems.

ASPEN provides a basic planning and scheduling capability for DFX. This basic capability takes several inputs:

1. A model of the spacecraft, operations constraints and rules (including for science experiments), and standard operating procedures
2. A specification of a problem, consisting of an initial spacecraft state, exogenous events, and desired goals (science and engineering).

Using these inputs, an automated planning and scheduling system generates plans/schedules which achieve the goals (if possible) while obeying the relevant operations constraints.

This paper describes an initial demonstration performed using the DCAPS scheduler [Rabideau et al. 1997], but current efforts to continue the DFX concept are based on the ASPEN scheduler [Fukunaga et. al 1997] However, the DFX concept is general, so any general purpose automated planner/scheduler would be usable within the DFX concept. However, as the central idea behind the concept is to allow experimentation with a wide range of spacecraft designs and mission scenarios, if the spacecraft models and mission scenarios are easily changeable and modular, this increases the usability of the DFX tool.

3. Demonstration on Pluto Express Pointing Alternative Designs

The first proof-of-concept design of the DFX tool is based on the Pluto Express (PX) sciencecraft. PX is a robotic reconnaissance mission to Pluto and its moon Charon. The Pluto mission will be unique in its approach. In order to minimize cost, while containing the risks associated with lower cost, the Pluto mission is being conceived as a pair of very small spacecraft, using, where possible, lightweight advanced-technology hardware components and advanced software technology. The Pluto mission plan calls for launch of two spacecraft early in the next decade toward encounters with Pluto and Charon around 2010 or later. The science goals of PX are to: characterize the global geology and geomorphology of Pluto and Charon, imaging both sides of each; map the surface composition; and characterize Pluto's neutral atmosphere, including composition, thermal structure, and aerosol particles.

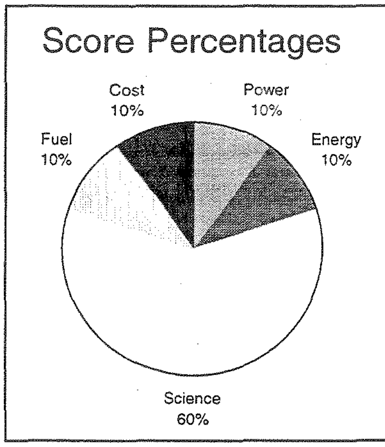
Pluto Express Model

The PX model is based on the assumption that the planetary and satellite encounter phase will drive the design. Because of the fast flyby velocity (12-20 km/s), the majority of science is performed within ±1 hour of encounter. Obviously, it is very important to optimize the science during these two hours. The preliminary model that we have built does not include the launch and cruise phases of the mission. Although there are two spacecraft, it is assumed their science will be identical. In reality, the two spacecraft encounters will be separated by 6 months and the science of the first will drive the science of the second. Indeed the science will be of the same type and with the same constraints so the assumption of identical science is valid. Another assumption in the model is that the start time and duration of both the Drop Zond (Charon probe) uplink and the spacecraft turns are fixed. This is a valid assumption because these times will not change between design options in the preliminary model.

The preliminary model consists of a common set of resources and a series of design options. Table 1 lists the common resources across all designs.

Quantity	Capacity	Resource	Power (W)	Mass (kg)
2	82 M RAM	local memory buffer		0.40
2	1 G RAM	mass memory buffer	2.15	0.40
2	n/a	general purpose heat sources	1.0	0.50
2	n/a	flight computers	5.22	0.40
1	n/a	integrated camera (UV, IR, visible)	6.0	6.90
1	n/a	hydrazine fuel tank	-	20.64
1	500 units	hydrazine fuel	-	16.5
6	n/a	delta-V thrusters	6.0	6.0
24	n/a	RCS thrusters	0.80	0.29
2	n/a	valve drive electronics (VDE) units	2.5	1.2
2	n/a	inertial reference units	4.00	0.40
2	n/a	stellar compass	0.50	1.5
1	n/a	high gain antenna	-	3.0
2	n/a	low gain antenna	-	1.0
2	n/a	telecommunications electronics	27.0	3.80

Table 1: Model Resources



RESOURCE	HOW IT IS SCORED	EFFECT ON SCORE
Power	$\frac{\text{Max. Power Available - Max. Power used}}{\text{Max. Power Available}}$	more margin = higher score
Energy	$\frac{\text{Total Energy Avail. - Total Energy used}}{\text{Total Energy Available}}$	more margin = higher score
Science	$\frac{\text{Science data captured}}{\text{allocated memory}}$	more science = higher score
Fuel	$\frac{\text{Fuel remaining after encounter}}{\text{Total Fuel Available}}$	more margin = higher score
Cost	Each resource cost 1 $ unit	scan platform is 1 unit

Table 2: Score Resource Computations

The primary design option of the preliminary model is the method of science pointing. The camera will be mounted on the body of the spacecraft and pointed with either the spacecraft control system (e.g., thrusters) or a movable mirror (called a scan platform). Each spacecraft slew between science frames requires 9 seconds that cannot be used for science data collection. The movable mirror only takes 1 second to change the science pointing. Due to the short encounter duration, the longer slew time for the spacecraft thruster based pointing greatly reduces the overall science return. In addition, the movable mirror option does not require the cold gas thruster system used for fine pointing slews. The absence of the cold gas thruster tank, plumbing, and thrusters reduces the overall mass of the spacecraft. The scan platform option adds additional complexities because it has moving parts.

The output of the DFX tool is a science data acquisition plan (SDAP). The SDAP is scored based on resource utilization and science output. An overall score is computed based on weighted contributions of each of the resources. For the PX mission, a preliminary scoring strategy was based on the resources of fuel, cost, power and energy each contributing 10% to the overall score, and science return contributing the remaining 60%. The computations of these resources and their influence on the score are summarized in Table 2. For the preliminary model, this strategy was arbitrarily chosen. Normally, the science community and the design engineers would develop a scoring strategy applicable to the mission.

Although the cost capability is built in to the scoring strategy, there is very limited information regarding the cost of the components. For this reason, the cost does not affect the score significantly. Likewise, the preliminary model for propulsion does not have thruster efficiency and propellant usage. The model currently assumes a fixed amount of propellant usage for each spacecraft turn.

Table 3 shows the direct comparison of the design options modeled in the demonstration, with the key pointing model difference highlighted in grey. Figure 2 shows the trace of the DFX tool output, which shows the score computation in detail.

Design Element	Design One	Design Two
Pluto Express Option	1D (RPS, solid upper rocket stage)	1D (RPS, solid upper rocket stage)
RPS	Amtec	Amtec
Drop Zond	included	included
Pointing mechanism	scan platform	cold gas thrusters
IRU	New Millennium development	New Millennium development
VDE	New Millennium development	New Millennium development
Stellar Compass	New Millennium development	New Millennium development

Table 3: Design Options Demonstrated

4. Future Plans

We are currently working on adding more detailed design information and design options to the model. Table 4 lists several design options that the PX project is currently pursuing. We are also planning to add the launch and cruise phases to the model. We would like to get good cost data for each of the spacecraft components and operations costs built into the model. We will be adding a

Options 1:

- RPS, solid upper rocket stage
- The RPS is an Amtec
- There is a Drop Zond included
- There is a scanning platform
- New Millennium development on IRU, VDE, and Stellar Compass

```
-----------------------------------
     Scoring Results
-----------------------------------
Allocated power:       85
Allocated energy:      627300
Allocated fuel:        500.0
Allocated memory:      200.0
Allocated cost:        100
Max. power used:       8
Total power switches:  46.0
Total energy used:     13096.0
Total fuel left:       498.0
Total data stored:     149.47
Total data taken:      149.47
Total observations:    48
Total cost:            36.0
---------------------
Power score:           90.6
Energy score:          97.9
Fuel score:            99.6
Cost score:            64.0
Data score:            74.7
==========================
Total Score:           80.05 / 100
==========================
```

Option 2:

- RPS, solid upper rocket stage
- The RPS is an Amtec
- There is a Drop Zond included
- There is no scanning platform
- New Millennium development on IRU, VDE, and Stellar Compass

```
-----------------------------------
     Scoring Results
-----------------------------------
Allocated power:       85
Allocated energy:      627300
Allocated fuel:        550
Allocated memory:      200.0
Allocated cost:        100
Max. power used:       8
Total power switches:  23.0
Total energy used:     13708.80
Total fuel left:       546.80
Total data stored:     135.62
Total data taken:      135.62
Total observations:    20
Total cost:            37.0
---------------------
Power score:           90.6
Energy score:          97.8
Fuel score:            99.4
Cost score:            63.0
Data score:            67.8
==========================
Total Score:           75.77 / 100
==============================
```

Figure 2: Trace of Output for Scoring the Two Alternative Pluto Express Pointing Designs

Trajectory	Telecommunications	Power
• Direct trajectory • JGA with solid • rocket motor – VVJGA – VVVJGA - JGA with solar • electric propulsion • and solar array	HGA: • Carbon-Carbon • Composite MGA: • Articulated • Passive Downlink: • Ka band • X band • both • optical comm. experiment	• 2 brick RPS • 3 brick RPS • solar array for solar electric propulsion

Table 4: Future Design Options

variable parameter space and running several scenarios over the space to identify candidate designs which optimize both science and operability. As mentioned earlier, we are going to work with PX engineers to determine a better scoring strategy.

5. Conclusions

This paper has described the novel application of using automated planning and scheduling technology to provide more concrete evaluations of alternative spacecraft designs and mission scenarios. In this application, called DFX, the planning/scheduling engine is used to produce baseline sequences for various combinations of spacecraft designs and/or mission scenarios. These sequences are then evaluated with respect to end mission success criteria such as science return, resource margins, and other metrics. This rapid evaluation is enabled by the automated nature of planning/scheduling technology and relieves the spacecraft and mission design personnel from the burden of manually constructing strawman sequences for evaluation. This enables the evaluation of a wider range of designs for both the spacecraft and overall mission. In that the spacecraft and mission specification can be made modular, construction of a wide range of spacecraft and mission designs can be facilitated. The DFX concept has been demonstrated using the DCAPS planning/scheduling engine on two pointing alternatives for the Pluto Express mission.

References/Sources

[Eggemeyer, 1995] W. Eggemeyer, "Plan-It2 Bible," JPL Technical Document, 1995.

[Fukunaga et al, 1997] A. Fukunaga, G. Rabideau, S. Chien, and D. Yan, "ASPEN: A Framework for Automated Planning and Scheduling of Spacecraft Control and Operations," Proceedings of the International Symposium on Artificial Intelligence, Robotics, and Automation in Space (I-SAIRAS97), Tokyo, Japan, 1997.

[Ghallab 1997] M. Ghallab, LAAS/CNRS, Toulouse, France, Personal Communication, September 1997.

[Pluto 1996a] Pluto Express FY 96 Annual Report, JPL Technical Document, 1996.

[Pluto 1995] Pluto Express FY 95 Annual Report, 1995

[Pluto 1996b] Pluto Express Power and Mass Worksheet, 1996.

[Pluto 1996c] Pluto Information Express Home Page, 1996.

[Price et al. 1996] H.W. Price, J.B. Carraway, S.E. Matousek, R.L. Staehle, R.J. Terrile, E.J. Wyatt, Pluto Express Sciencecraft System Design, JPL Technical Document, 1996.

[Rabideau et al. 1997] G. Rabideau, S. Chien, T. Mann. C. Eggemeyer, J. Wilis, S. Siewert, P. Stone, "Interactive Repair-based Planning and Scheduling for Shuttle Payload Operations," Proceedings of the IEEE Aerospace Conference, Aspen, CO, 1997.