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A Market-Based Mechanism for Allocating Space Shuttle Secondary Payload Priority

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Abstract

This is an investigation into the design of a market-based process to replace NASA's current committee process for allocating Shuttle secondary payload resources (lockers, Watts and crew). The market-based process allocates budgets of tokens to NASA internal organizations that in turn use the budget to bid for priority for their middeck payloads. The scheduling algorithm selects payloads by priority class and maximizes the number of tokens bid to determine a manifest. The results of a number of controlled experiments show that such a system tends to allocate resources more efficiently by guiding participants to make resource and payload tradeoffs. Most participants were able to improve their position over NASA's current ranking system. Furthermore, those that are better off make large improvements while the few that do worse have relatively small losses.

Keywords: mechanism design, auctions, scheduling

JEL Classification: C92

I. Introduction

Typically, when different parts of an organization require similar resources to produce their outputs, those resources become centrally financed and managed. There are many examples of these types of resources in practice: meeting rooms, networks, motor pools, etc. These resources tend to be managed in a bureaucratic fashion in which allocation decisions are made in committee settings with administrative negotiations. As the system becomes more and more congested, meeting times increase with many appeals to upper management. Two types of responses to congested facilities are usually tendered by facility operators: 1) pleas to users to reduce their demands[1] and/or 2) the development of algorithms to heuristically solve the complex scheduling problem based on information from users concerning priorities and resource requirements.

Committee allocation is used in the manifesting of secondary payload resources aboard NASA's fleet of Space Shuttles. Secondary payloads are those payloads that are stored in the middeck lockers on the Space Shuttle. Each locker can accommodate payloads that are 44 cm (17.3 in) wide by 25.4 cm (10 in) high, have a maximum weight of 24.5 kg (54 lbs.) and may not require more than 130 watts on orbit. The current NASA approach to manifesting secondary payloads has users from the various NASA organizations, known as User Codes, submit requests for the number of lockers needed to accommodate their payloads. These requests are then processed by a second group of individuals, known as schedulers; to produce the flight manifests for the upcoming Shuttle flights.

Once the manifest is produced, a large number of meetings with representatives from the various User Codes are convened to debate the merit of the manifest, the reasons for omissions of some of their payloads, and the justification for including others. These meetings are held biweekly and typically last half a day. As a result of each meeting, schedulers may be required to redo the manifests, which will in turn produce another set of pleased and disappointed users.

To alleviate the cycle of manifest, meeting, re-manifest, meeting, etc., the Office of Space Utilization (Code MO) approved the development and test of a prototype, electronic, market-based system to assist in resolving scheduling conflicts.[2] The basic tenet of a market-based approach is that allocation decisions should be made considering the information that describes the circumstance of each user. Each user must make trade-offs among their demands based on the relative scarcity of resources (see Clearwater et al. (1995) for details of a market-based approach for the thermal control of an office building). This paper proposes a mechanism to allocate secondary payload resources and reports on a series of experimental tests of that design using the current process as a benchmark.

The research presented in this paper treads on new ground in the area of applied mechanism design. In contrast to the previous work in this area on market design (see Plott (1994) for a review) this paper investigates the use of markets within a firm to resolve resource allocation problems. As such it incorporates new variables into the mechanism design. In particular, we implicitly consider organizational constraints in the mechanism design. First, there was a constraint imposed on us that did not allow monetary transfers across organizational units. This caused us to venture into the use of fiat money or tokens to obtain qualitative trade-off information. Second, to minimize transition costs, we were to focus on mechanisms that assign priority as opposed to direct resource allocation. Lastly, the environment associated with the Shuttle manifesting is very complex. This required the creation of new algorithms for scheduling. The sequential packing algorithm used in the experiments has not been used before and had to be specifically programmed for these experiments.

In the next section we supply some background on the Shuttle manifesting process and the technical inputs and outputs required to create a manifest. Next, we describe the mechanism design process we used to formulate the new allocation process. We then discuss our experimental design and testing methodology. A section containing the results of the experiments follows. We end with some observations and describe the current status of this market-based mechanism.

II. Background

The manifest for secondary payloads is typically formulated for a one-year period and is finalized a year before the first scheduled flight in the period. Early in the process the availability of resources over the period is determined. Resources are Shuttle specific since each Shuttle will have different capabilities over the horizon. Let $\boldsymbol{X}_i = \langle x_i^1, x_i^2, \ldots, x_i^n \rangle$ be the vector of capacities/attributes of each of the resources available for each Shuttle $i = 1, \ldots, m$ over the planning horizon. These resources include the number of lockers, electrical power and crew time, and common resources such as altitude and inclination. In addition, there is an interaction between these resources since, for example, less weight can be lifted to higher orbit inclinations.

Payloads are sponsored by various User Codes. A User Code sponsors a payload by providing funding for design, development and operations. We define a payload by its resource requirements. Let $\boldsymbol{Y}_{jk} = \langle y_{jk}^1, y_{jk}^2, \ldots, y_{jk}^n \rangle$ be the vector of Shuttle resources required by payload $j = 1, \ldots, J$ of code $k = 1, \ldots, K$.[3]

The manifesting process takes items from the list $\boldsymbol{Y}_{jk}$ and assigns them to Shuttle flights $\boldsymbol{X}_i$ using some rule. Some examples are (1) maximize resources used, (2) minimize the number of appeals to upper management, etc. The rule currently used by the schedulers begins with a prioritized list from the users. The schedulers translate that into one list and then go down the list fitting them onto Shuttles that have the required resources and attributes. Occasionally this is modified since schedulers also want to fully utilize resources and get as many "high" priority payloads on the list as possible.

We can represent the manifesting decision using the objective function $U(Y_{11}, \ldots, Y_{HL}; X_1, \ldots, X_m)$ of the manifesting organization. Thus, the manifest choice is a multiple knapsack problem. They *choose an allocation rule* Γ to:

$$\begin{array}{ll} \text{maximize} \quad U\left(\Gamma_{11}^1 \cdot Y_{11}, \ldots, \Gamma_{JK}^m \cdot Y_{JK}\right) & \\ \text{subject to} & \\ \sum \sum \Gamma_{jk}^i \cdot \boldsymbol{Y}_{jk} \leq \boldsymbol{X}_i & \forall i \text{ (resource use by payloads must fit Shuttle capacity)} \\ \Gamma_{jk}^i \varepsilon \{0, 1\} & \forall i, j, k \text{ (the payload is either on or off the manifest)} \\ \sum_i \Gamma_{jk}^i \leq 1 & \forall j, k \text{ (a payload can be on one Shuttle not across Shuttles)} \end{array}$$

This particular problem is a complex integer-programming problem. To solve it NASA schedulers use instincts, heuristics and rules of thumb. In our conversations with the Shuttle schedulers we found that they equate optimal use with the condition where the manifest uses all resources to capacity. The only other information that is provided to the schedulers is the "priority" assigned by the Codes for their own payloads. Given this qualitative information, it could only be an accident that the schedulers arrive at a Pareto optimal allocation. What is being maximized is the value as perceived by the schedulers and not the science being generated. One way to create a better manifest is to create a different process that extracts the appropriate value information from the user, so schedulers can create a "better" fit of the resources.

III. Mechanism design

Suppose that instead of the general priority information given by users, the scheduler knew the relative values a user placed on each of its payloads. Specifically, let V_{jk} denote code

k's value for payload j. Suppose also that the scheduler would like to maximize the returns to the users while maintaining some sort of "fairness criteria" which can be defined as a constraint on the manifest chosen:

$$\begin{aligned}
&\text{maximize} \quad \sum\sum\sum \Gamma^i_{jk} \cdot V_{jk}\\
&\text{subject to}\\
&\sum\sum \Gamma^i_{jk} \cdot \boldsymbol{Y}_{jk} \le \boldsymbol{X}_i \quad \forall i \text{ (resource use by payloads must fit Shuttle capacity)}\\
&\Gamma^i_{jk} \varepsilon \{0, 1\} \quad \forall i, j, k \text{ (the payload is either on or off the manifest)}\\
&\sum_i \Gamma^i_{jk} \le 1 \quad \forall j, k \text{ (a payload can be on one Shuttle not across Shuttles)}\\
&U\left(\Gamma^1_{11} \cdot Y_{11}, \ldots, \Gamma^m_{JK} \cdot Y_{JK}\right) \ge U \text{ (fairness of the manifest)}
\end{aligned}$$

That is, if the scheduler knew values of the users he could incorporate this into his optimization process.

The main focus of applied mechanism design in economics (see Ledyard (1993) for a review of this method) is to create a mechanism in which the rules of the game provide the proper incentives to participants so that outcomes meet specified objectives. The idea is simple. Participants bring their own information and valuations to the process. The process is then conducted and the participants interact with each other through the mechanism. The interaction between individual behavior and the mechanism produces an allocation. Operating the same mechanism on a different constellation of values will, generally, produce a different allocation. Operating a different mechanism on the same constellation of values across individuals will, generally, also produce a different allocation. We refer to the relationship a mechanism creates between the particular constellation of values and the allocation as the *performance of the mechanism*.

With this background in hand, we now describe the mechanisms we considered along with their basic properties.

IV. Mechanisms tested

The market-based alternative we propose to the current mechanism allocates resources among competing Shuttle secondary payloads using a priority system. We begin this with a description of the current mechanism, which will be our baseline when we analyze the results. We then describe the new mechanism.

A. Characterizing the current allocation mechanism

In the current approach to scheduling, participants simply identify a rank for each of their payloads. Let $r_{jk} \in \{1, 2, 3, 4, \ldots, R_k\}$ denote the rank for payload j of code k. If $r_{jk} < r_{j'k}$ then payload j should be manifested before j' for Code k, if enough resources are available.

If $r_{jk} = r_{j'k}$ then the scheduler can choose either j or j' to be manifested. The scheduler then tries to solve:

$$\begin{array}{ll}
\text{maximize} \quad U\left(\Gamma_{11}^{1} \cdot Y_{11}, \ldots, \Gamma_{JK}^{m} \cdot Y_{JK}\right) & \\
\text{subject to} & \\
\sum \sum \Gamma_{jk}^{i} \cdot \boldsymbol{Y}_{jk} \leq \boldsymbol{X}_i & \forall i \ \text{(1) (resource use by payloads must fit Shuttle capacity)} \\
\Gamma_{jk}^{i} \varepsilon \{0, 1\} & \forall i, j, k \ \text{(the payload is either on or off the manifest)} \\
\sum_i \Gamma_{jk}^{i} \leq 1 & \forall j, k \ \text{(a payload can be on only one Shuttle)} \\
\text{If } r_{jk} < r_{j'k} \text{ then } \Gamma_{jk}^{i} \geq \Gamma_{jk}^{i} \text{ unless (1) is violated} &
\end{array}$$

This type of mechanism is sometimes called an *ordinal ranking scheme* and has the properties that it is a dominant strategy to reveal your true ranks. But even with complete revelation the outcome need not be efficient (see Olson (1993) for details). One major inefficiency that arises from this ordinal ranking system is that several lower ranking payloads, that in total use less resources than a higher ranked resource, provide more science benefit than the higher ranked payload. It is this inefficiency along with the high transactions cost nature of negotiations that we seek to address.

The basic rule of thumb used by the scheduler is to manifest as many of the highest priority payloads as possible, utilize as much of the Shuttle resources as possible, and try to be "fair" to the individual User Codes. "Fair" typically means to make every attempt to manifest payloads proportional to the number of requests by each Code (we will represent this variable as W_k).[4] Thus, the general structure could be written as:

$$\begin{array}{ll}
\text{minimize} \quad \sum \sum \sum \Gamma_{jk}^{i} \cdot r_{jk} & \\
\text{subject to} & \\
\sum \sum \Gamma_{jk}^{i} \cdot \boldsymbol{Y}_{jk} \leq \boldsymbol{X}_i & \forall i \ \text{(resource use by payloads must fit Shuttle capacity)} \\
\Gamma_{jk}^{i} \varepsilon \{0, 1\} & \forall i, j, k \ \text{(the payload is either on or off the manifest)} \\
\sum_i \Gamma_{jk}^{i} \leq 1 & \forall j, k \ \text{(a payload can be on only one Shuttle)} \\
\dfrac{\sum_i \sum_j \Gamma_{jk}^{i}}{\sum_i \sum_j \sum_k \Gamma_{jk}^{i}} \geq W_k & \text{(proportional fairness)}
\end{array}$$

Due to the ranking nature of this process the solution is not unique. Furthermore, the fairness constraint describe above does not solve the inefficiencies of the ordinal ranking process and can create further inefficiencies by the arbitrariness of the constraint. In practice this means appeals occur regularly and much time is spent in negotiation over possible changes to the proposed manifest.

B. A bidding process

Instead of soliciting ordinal rank information and imposing a general notion of fairness, a different type of mechanism can be created similar to an auction mechanism for private goods (see Rassenti et al. (1982), Banks et al. (1989), and Wohl (1997)). The major organizational constraint placed on us was that we must use priority classes for selecting payloads. This request came from Shuttle operations management who insisted that due to the standing process of eliciting priorities, the transition costs would be prohibitive and political roadblocks would be insurmountable for any process that did not elicit simple priorities. In addition, they also made it clear that budget transfers would be out of the question. This constraint is mainly a product of the budgeting cycle in Washington. Codes would have to make fiscal year requests for funds to bid for Shuttle resources before they knew the required bid. If one waited until the bidding was complete defaults would likely occur. Thus, the use of internal money was the only practical means of providing incentives. The mechanism we proposed has the following structure. Each code is given a budget of tokens $B_k(t)$ over several planning horizons $t = 1, 2, \ldots, T$. This budget is used to secure priority on the Shuttle manifest. In particular, each participant uses their budget to bid for limited positions in a priority queue. Let $P_h \varepsilon \aleph$ denote the number of positions available in priority class $h = 1, \ldots, H$. For example, if $P_1 = 5$ this means that there are at most five slots available in priority class 1. Thus, at most five payloads can be accommodated in priority class 1. Let b_{jh} denote the bid on payload j for priority h. Only the highest bids are accepted. Thus, the *standing bids* S_h for priority class h are such that $|S_h| \leq P_h$ and $\sum_{b_{jh} \in S_h} b_{jh} \geq \sum_{b_{jh} \in D_h} b_{rh} \forall |D_h| \leq P_h$. That is, only the highest P_h bids are accepted in priority class h. However, not all bids may be manifested since resource constraints must be considered. The scheduling algorithm uses bids to rank payloads and is applied sequentially to priority classes as follows:

Beginning with *priority class 1* the algorithm solves:

$$\text{maximize} \quad \sum \sum \sum \Gamma^i_{jk} \cdot b_{jk1}$$

$$\text{subject to}$$

$$\sum \sum \Gamma^i_{jk} \cdot \boldsymbol{Y}_{jk} \leq \boldsymbol{X}_i \qquad \forall i \text{ (resource use by payloads must fit Shuttle capacity)}$$

$$\Gamma^i_{jk} \varepsilon \{0, 1\} \qquad \forall i, j, k \text{ (the payload is either on or off the manifest)}$$

$$\sum_i \Gamma^i_{jk} \leq 1 \qquad \forall j, k \text{ (a payload can be on only one Shuttle)}$$

$$\sum \sum \sum \Gamma^i_{jk} \leq P_1 \qquad \text{(capacity of slots in priority class 1)}$$

Let the solution to the above problem be represented by the ${\Gamma^i_{jk}}^{*1}$. The algorithm then takes the resource requests of the priority 1 selected payloads and makes them constraints for the next stage of the algorithm. In this way, higher priority payloads that fit the resource constraints will always be accommodated before lower priority class payloads. This also means that submitting bids for the same payload to lower priority classes is futile since lower ranked payloads will not make the manifest if higher priority payloads with the same resource configuration could not make the manifest. Thus, for *priority class* $h + 1$ we solve:

$$\begin{aligned}
&\text{maximize} \sum\sum\sum \Gamma^i_{jk} \cdot b_{jk(h+1)} \\
&\text{subject to} \\
&\sum\sum \Gamma^i_{jk} \cdot \boldsymbol{Y}_{jk} \leq \boldsymbol{X}_i \quad \forall i \text{ (resource use by payloads must fit Shuttle capacity)} \\
&\Gamma^i_{jk} \varepsilon \{0, 1\} \qquad\qquad\quad\;\; \forall i,\ j, k\, k \text{ (the payload is either on or off the manifest)} \\
&\sum_i \Gamma^i_{jk} \leq 1 \qquad\qquad\quad\;\; \forall j, k \text{ (a payload can be on only one Shuttle)} \\
&\Gamma^i_{jk} = \Gamma^{i\ *h}_{jk} \quad \text{if } \Gamma^*_{jkh} = 1 \text{ for some } h < h + 1 \\
&\text{(payloads manifested from higher classes are always in the new manifest)}
\end{aligned}$$

In addition to solving the integer programming problems above, the market-based mechanism uses a feedback procedure to allow participants to revise their bids. This feedback has been shown to be useful in getting systems to move to better outcomes and is similar to the process used in the current Federal Communications Commission spectrum auctions (see McAfee and McMillian, 1996; Milgrom, 1998). This process moves in rounds. At the beginning of a round the winners from the previous round in each priority class are posted. New bids are accepted but must beat the standing bids in order to be accepted. The process stops when no new manifest is found.[5]

One design issue for this auction remains: the assignment of bidding budgets. Little has been written on this but three methods have been suggested that seem reasonable:

1. Grandfathering based on past use might be a good rule for the short-run. If past decisions are a good proxy for demand then token allocations based on past usage of resources would, in principle, make no user worse off.
2. Correlating bidding budget amounts to design and development budgets for secondary payloads could be a proxy for the agency's derived demand for these payloads. This would be an easier allocation process since there is only one dimension (budget) to consider. However, this rule would provide incentives to inflate design and development budgets to increase schedule priority.
3. A committee could be created to allocate bidding budgets. This is the usual approach. It allows information about future budgets and programs to be integrated in the selection process.

The main item to notice about these processes, is that the difficult token budget allocation decision is made "once" instead of revisiting each manifest to see if it meets general preferences.

In the experiments below we used equal budget amounts in one set of experiments and an assignment of budgets given by Shuttle management in the other set of experiments.

V. Experimental design

How can one compare the differences between the auction mechanism and the current process? When the mechanism under review is so complex that theoretical analysis is difficult, experiments can be used to learn about the mechanism's properties.[6] Experiments in economics provide a type of "wind tunnel" within which to test mechanism designs. The tests can be used to identify potential design flaws of new mechanisms in new environments. The process is similar to the testing of airfoils in wind tunnels or the testing of hull shapes in towing tanks. One first simulates the environment, in our case by inducing the constellation of participants' valuations and the information they each have about these valuations. Then a mechanism is provided and participants operate within the testbed environment. Performance is measured. With enough variation in the environments and enough variation in the mechanisms one can begin to reach some conclusions about details in design that affect performance. Hunches and arguments loosely based on incomplete theory can be replaced by data. It is this form of experimentation that we report on here.

A. Environments tested

The experiments conducted in this paper used two types of economic environments. The first sets of values were designed to see how the process would work in "simple" congested cases. If the process doesn't work in the simple cases a rethinking or redesign would certainly have to occur before trying it outside the laboratory. The second set of values was used as a "simulation" in which past payload resource use and Shuttle capacities were given to us by Code MO engineers to see how the process worked in a larger scale environment.

i. Simple environments. Our first set of experiments were designed to provide isolate the inefficiencies of an ordinal ranking scheme by making the sum of the value of less resource intensive payloads more valuable than a single highly valued resource intensive payload. We designate these experiments as "simple" because they were intentionally made less complex relative to the standard Shuttle manifesting. In particular, we created two different environments that used three planning horizons with two Shuttle flights for each period. Each Shuttle $i = 1, 2$ supplied three resources ($x_{\text{Lockers}}, x_{\text{Watts}}$ and x_{Crew}) to payloads (see Appendix A for details). Each subject was paid, in cash, the value of his or her payloads that were actually included in a final manifest for a period. Each subject k received a sheet listing the values V_j of his payloads along with its resource requirements Y_j. Subjects did not know the values of other participants. The values used in the experiments can be found in Appendix A. Given the private value and common resource information, participants made decisions in the ordinal ranking and bidding mechanisms described above.

Prior to the start of each market, subjects were asked to submit a ranking of their payloads from 1 (highest priority) to n (lowest priority). They were told that to begin we would select a random ordering of the participants. Beginning with the first person in that order we would take their highest rank payload and try to fit it in the manifest, it if it did not fit we would go to the next payload on their priority list until a payload fits or the list was exhausted. If a subject listed several payloads with the same priority, we took this to mean that it was under the discretion of the scheduler to pick any of those payloads as long as they fit within the available resources. The order was then reversed for the next pass through the manifest (similar to a little league draft). The actual manifest was developed by a single human scheduler (an engineer at the Jet Propulsion Laboratory) who used his best intuition and rules to manifest according to the basic rules described above. This scheduler created a manifest for each of the three periods using the rank information. In each experiment subjects only participated in one session of the ranking mechanism. They then entered the market mechanism.

In the market mechanism, subjects placed bids in priority classes. The bids were used to select payloads as described in Section III. The process proceeded over rounds in which subjects could update their bids. Any unused budgets of scheduling points could be carried over to future flight manifests. However, the process would end after 3 periods, at which time unused budgets would expire as worthless.

For the auction process, one can define a competitive market equilibrium (CE) vector of priority point prices that must be paid for resources used by a participant. A CE set of prices $P = (P_{\text{lockers}}, P_{\text{Watts}}, P_{\text{crew}})$ has the property that if each individual maximizes their values given these prices and their budgets, demand and supply equate. These prices show the relative scarcity of each resource. In Case 1, the price of Watts was zero so that they were not scarce at all while the relative prices of lockers and crew were equal. In Case 2, all resources were scarce with the relative price of Lockers being the largest.

ii. Simulation. To test the mechanisms in a Shuttle specific environment, this second set of experiments used data from actual payloads flown on past Shuttle flights. In these experiments, there were six Shuttle flights per period and the experiment lasted two periods. The budget amounts for each participant was selected by Code MO personnel. Subjects participated in the rank mechanism and the market-based system in this environment. The major difference between the simple congestion cases and this environment was the increased number of payloads and flights. Participants in these experiments were experienced and the experiment was conducted remotely. That is, participants were located throughout the campus of the California Institute of Technology and would send in their bids twice a day over the Internet to our central Website.[7] The actual values used in the experiments can be found in Appendix A.

B. Design summary

All of the experiments were conducted at the California Institute of Technology using the student population as the subject pool. The market-based mechanism was computerized and resided on the Internet. Subjects were initially trained in a 90 minute session to familiarize them with how to determine their payoffs, use the computer system and participate in a practice period including the ranking mechanism. They were paid a flat $20 fee for their participation in the practice session. From the set of trained subjects we recruited 5 subjects for each experiment reported here. Each experiment lasted approximately 2 hours. Only one realization of the ranking and auction was conducted per experiment. Each simulation used 5 experienced subjects, i.e. subjects who had participated in the simple environments. Table 1 lists information about each environment.

Table 1. Experimental design.

Environment	Number of experiments conducted	Subject pool
Case 1	3	Caltech
Case 2	3	Caltech
Simulation	2	Caltech, experienced

VI. Results

In this section we show the comparative results between the ranking system and the market-based system for each environment. We examine how each process utilized the available resources. This measure will tell us how well a process packs the Shuttles but will not tell us how well the process delivers on the item most crucial to participants—value. To do that, we will measure the relative payoff positions for each subject. The results of these exploratory experiments are based on at most three experimental observations for each environment. Thus, we do not supply any classical statistical tests. However, our intention with these experiments was not to provide large sample tests. Our investigation is more a proof of concept than what some would consider “theory testing.” We point out however, that theory testing does not necessarily imply large samples but how posterior beliefs are updated after observing experimental outcomes. For the questions we are interested in answering, our small sample is not an issue.

A. Simple environments

Recall that in the ranking mechanism, subjects had to give a ranking of payloads with the understanding that higher priority payloads would be selected first to fit within the manifest before lower priority payloads. The first two results describe the resource use pattern in the rank mechanism.

Result 1: In the ranking mechanism subjects prioritized their payloads in a one-to-one correspondence with the values on their sheets (higher valued payloads were ranked higher even though that was not necessary).

This result is not surprising, since participants have no means of assessing values in light of the relative costs of the various resources used.

Result 2: Although the relative CE price of Lockers and Crew hours in case 1 was one, there was more demand for Crew than Lockers.

When the scheduler looked at the requests by the highest priority payloads he noticed that Crew time would run out before the other resources for the case 1 preferences. In particular,

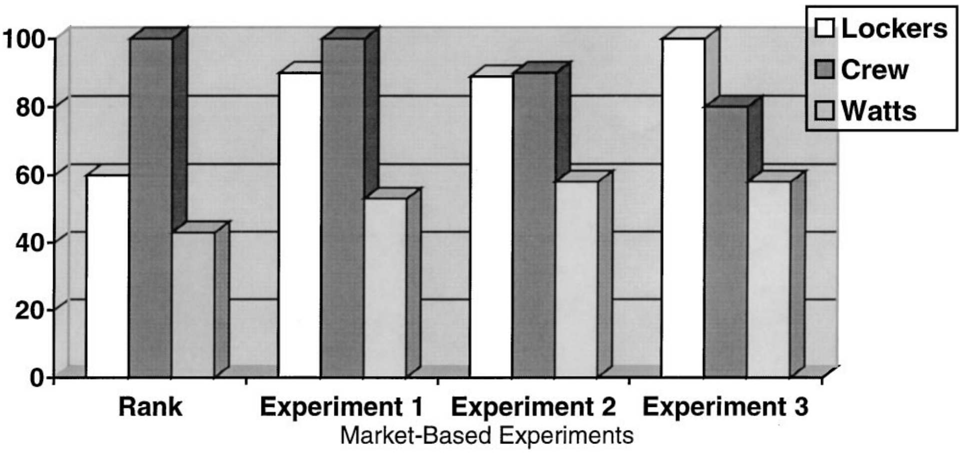

Figure 1. Resources used in ranking vs. market-based approach: Case 1.

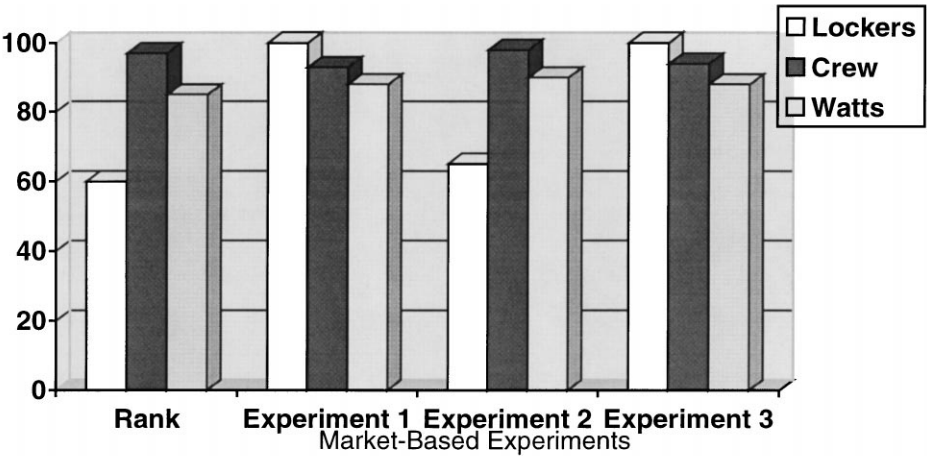

Figure 2. Resources used in ranking vs. market-based approach: Case 2.

when crew usage was at 100% of capacity by the highest ranked payloads, locker capacity was only used at a 50% of capacity (there was an abundance of Power available and only 30% of capacity was requested).

Result 3: In cases 1 and 2, the market-based-system does a better job of utilizing lockers and Watts than the ranking system.

Figures 1 and 2 shows the percent of capacity utilized by the final manifest for each treatment. We pooled the ranking results because they were identical across the three experiments. The ranking mechanism always used crew hours to capacity. Even though the

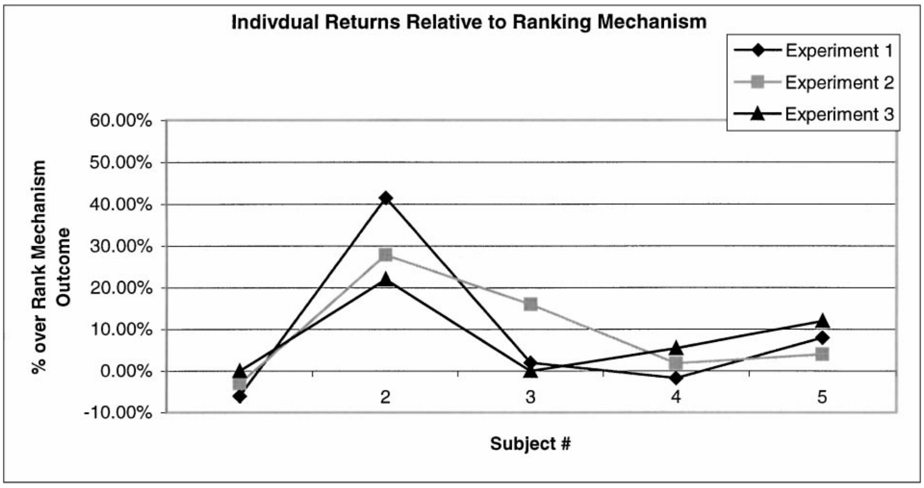

Figure 3. Percent increase in payoff for each subject using the market-based approach over the ranking scheme: Case 1.

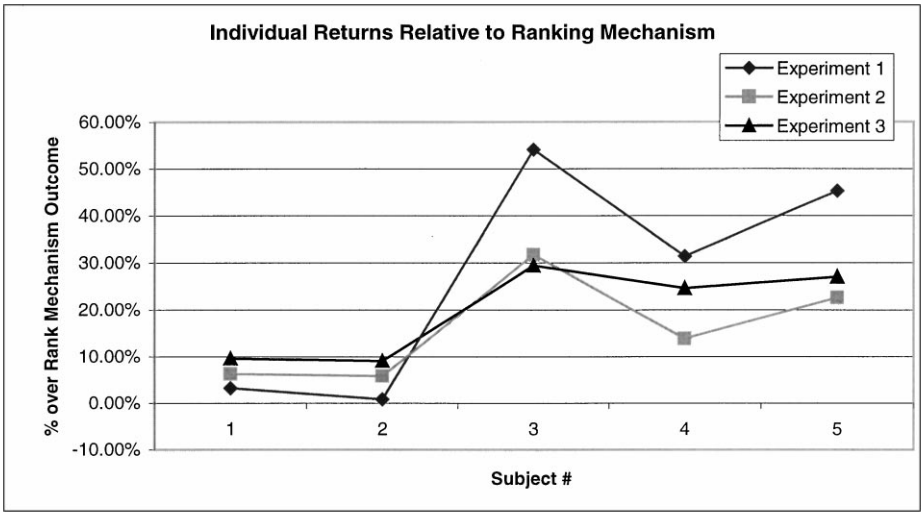

Figure 4. Percent increase in payoff for each subject using the market-based approach over the ranking scheme: Case 2.

relative CE price between lockers and crew was one, it appeared to the scheduler that from the rank requests crew hours were the binding resource. The market-based mechanism seems to do a better job of tracking this relative scarcity between lockers and crew.

Result 4: Most participants are better-off with the market-based system over the ranking scheme.

Table 2. Average token prices.

Environment	Priority 1 prices	Priority 2 prices	Priority 3 prices
Case 1			
Periods 1 and 2	75	47	4
Period 3	102	54	21
Case 2			
Periods 1 and 2	69	46	10
Period 3	98	73	18

Figures 3 and 4 show the ratio, in percentage terms, of the market-based payoff to the payoff from the rank mechanism for each subject. In case 1, subject 1 averaged a loss about 4% of his payoff from going to the market-based mechanism. All other subjects averaged a 12% increase in payoffs in going from the rank mechanism to the market-based mechanism in case 1. For case 2, all subjects were made better off (the range was from .5% to 54%).

In the market-based mechanism subjects bid for priority. We should expect that prices for the same level of priority should be the same and that higher priority classes should have higher prices. In our experiments we had only three priority classes. Priority 1 was the highest class and priority 3 was the lowest class. In addition, the experiment consisted of three periods. Bidding for priority began in Period 1. An unused budget could be carried over to the next period (Period 2) in bidding for priority. Finally, all unused budgets would be carried over to the last period (Period 3) and the experiment ended after that period.

Result 5: Priority prices are monotonic by class. Priority 1, prices averaged 50% more than priority 2 prices; priority 2 prices averaged over 4 times the priority 3 price. Recall that in the last period, bidding budgets expire and are therefore worthless. This results in a phenomenon of inflated prices in the last period.

Table 2 shows the average token price submitted for each priority class and period. The prices are similar across the cases. Figures 5 and 6 show the time series prices by priority and period. It is easy to see from these graphs that prices vary significantly within each priority class.

B. Simulation

Our last series of experiments were designed to be “more” realistic as perceived by the managers of Code MO. In particular, we requested that the managers review past manifests and provide us a list of payloads across Codes and Shuttle capacities that would be representative of the kind of requests they usually face. Furthermore, we asked them to provide us with a set of budgets for each Code that they thought would be “reasonable.” We called this larger set of conditions our simulation.

Result 6: In the ranking mechanism subjects prioritized their payloads in a one-to-one correspondence with their values. There was significant excess demand in all dimensions.

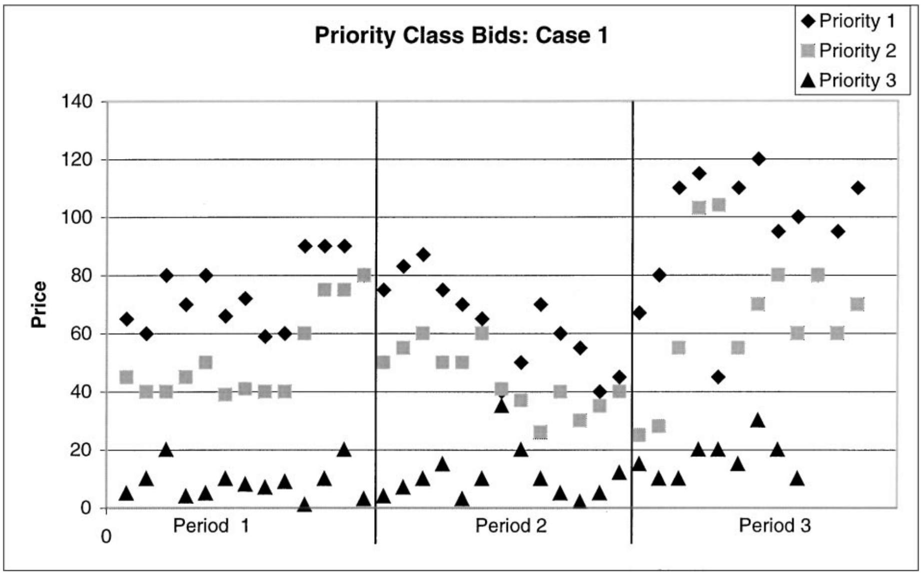

Figure 5. Priority prices in case 1.

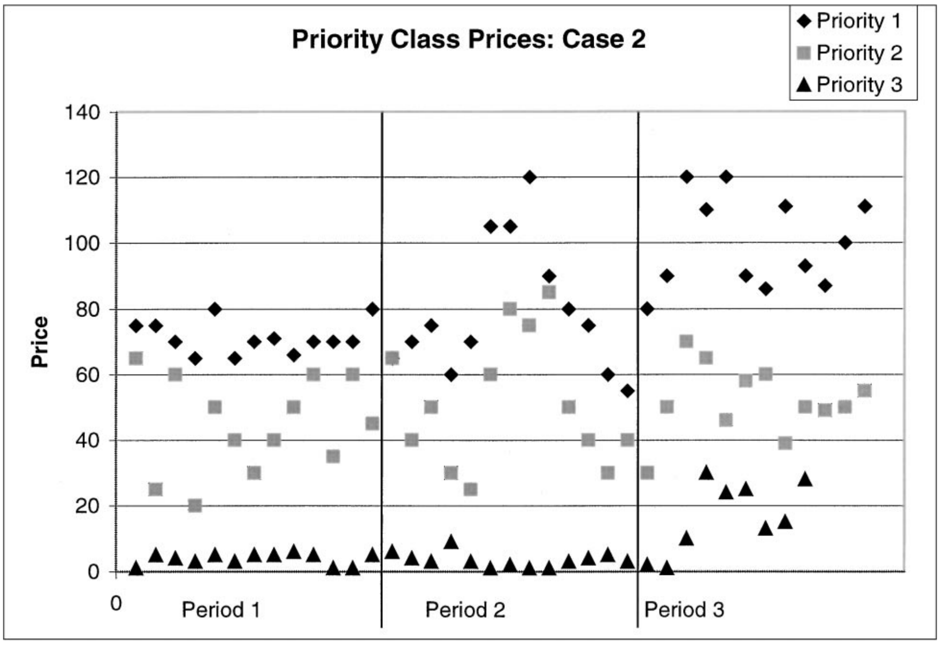

Figure 6. Priority prices in case 2.

Table 3. Ranking requests.

Experiment	Use of lockers as a % of capacity	Use of power as a % of capacity	Use of crew as a % of capacity
Simulation	132	148	151

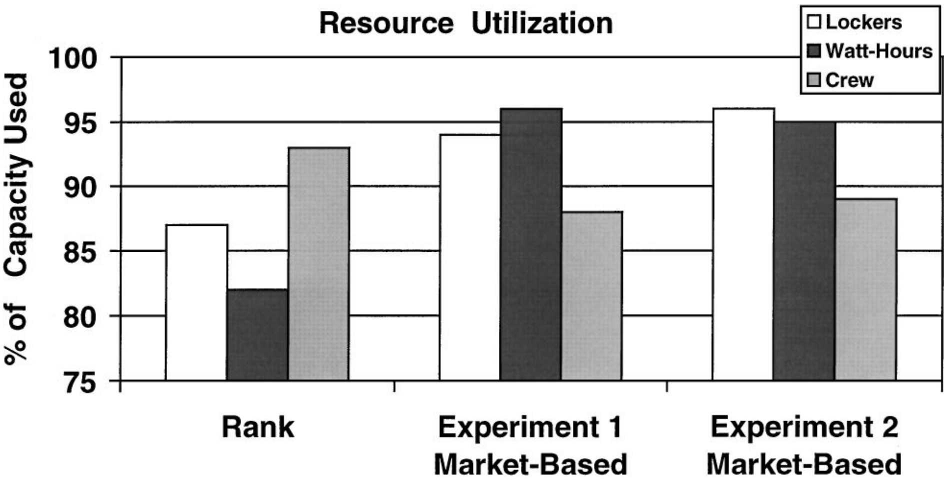

Figure 7. Comparison of resources used in a ranking vs. market-based approach.

Table 3 and figure 7 show the actual resource used. Table 3 shows the sum of all resource requests divided by the sum of all the Shuttle capacities. On a relative basis Crew looks the most dear followed by Power and then Lockers. The Competitive Equilibrium prediction would have ranked resource in the following order: Lockers, Crew and then Watts.

Result 7: The market-based-system does a better job of utilizing lockers and Watts than the ranking system.
Result 8: Participants are typically better off with the market-based system.

Figure 8 shows the payoff outcomes of the market-based mechanism relative to the relative to the rank mechanism. Every subject except one was made better-off with (increased payoffs ranging from 2% to 21%). The DoD subject did the worse out of all the subjects with the market-based mechanism. Coincidentally, that subject had the lowest budget of tokens. Whether this is a universal feature of this mechanism remains an open question.

Result 9: Priority 1, prices averaged 140% more than priority 2 prices and priority 2 prices averaged over 5 times the priority 3 price. The last period effect still arises.

Figure 9 shows the time series of the prices for each priority class and period. Three features of the data are replicated here from the simple experiments previously presented:

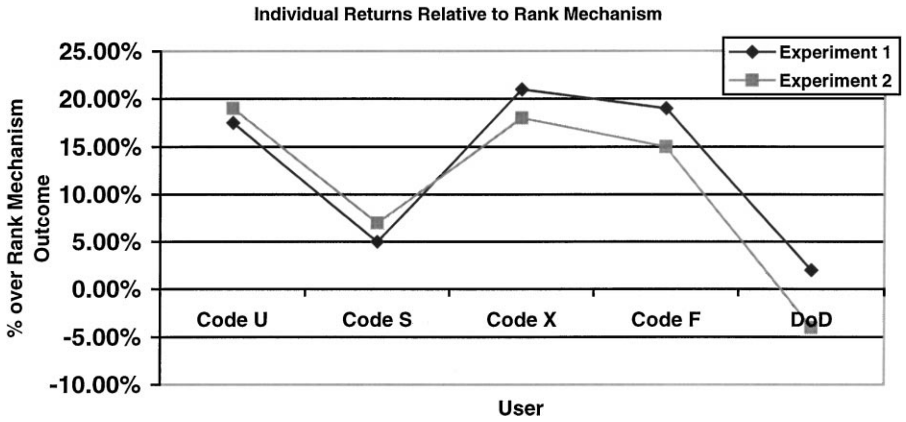

Figure 8. Percent increase in payoff for each subject using the market-based approach over the ranking scheme.

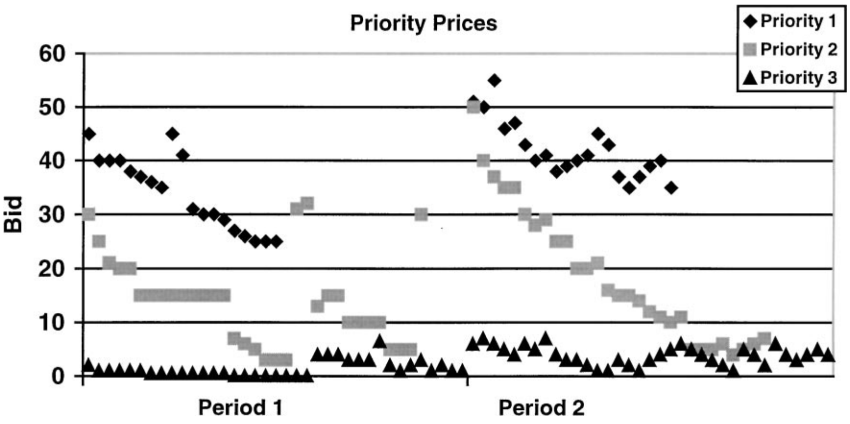

Figure 9. Priority prices in the simulation environment.

1. Higher priority classes have higher prices
2. Prices are higher in the last period across all priority classes
3. Prices vary significantly within each priority class

VII. Summary

In this paper we describe the results of an investigation of a market-based process to replace NASA's current committee process for allocating Shuttle middeck resources. The market-based process allocates budgets of "funny money" to NASA User codes, managers of each code in turn use the budget to bid for priority for their middeck payloads. The scheduling algorithm selects payloads by priority class and maximizes the number of points bid to determine a manifest. The results of the experiments show that such a system tends to allocate resources better because participants make resource and payload tradeoffs. Most participants were able to improve their position over NASA’s current ranking system. Furthermore, those that are better off make large improvements while the few that do worse had relatively small losses. One issue that deserves some attention is the last period inflation of prices due to the fact that the budgets expired worthless. On the one-hand, this did not seem to damage efficiency, but it creates an unwarranted price volatility. In practice, this means that management should understand that changing the supply of tokens will create volatility. If the process has a long life this will likely not be a problem. We could have used a probabilistic ending rule but we did not want to complicate our design any more than necessary.

One of the major constraints that was imposed on us was the use of priority classes. The subjects had very little trouble bidding in this system. In general, the market-based process ran smoothly, but it fell short of realizing the full trade-off potential among payloads. As we noted above, the mechanism allocates priority among payloads but not resource use. Thus, large high priority payloads tend to obtain a relatively large number of resources for the same “price” as smaller high priority payloads. The main work of the mechanism occurs in the lower level priority classes where resource competition and fitting are crucial. There is an issue concerning the number and size for each priority class and their effect on science value distributions. In order to squeeze more efficiency out of this system we suggest that a new process be tested in which each priority class is constrained by vector of resource capacities as opposed to slots. Thus, payloads would have to fit within the resource constraints and the optimization can take that into account when maximizing. This still maintains the priority designations but should provide better “price” signals on relative scarcity.

In analyzing Shuttle operations data we noticed that differences between planned and actual available capacities were typical. When actual available capacity is announced, a contentious re-manifesting process occurs. If schedulers had the bid information from the market, then this information could be used to re-manifest the payloads. This is a natural output of the market process.

The market-based mechanism we presented in this paper was reviewed by Shuttle management and users in October of 1997. The Shuttle user community was not entirely enthusiastic about changing the current process but had no real objections to this market-based approach. The Shuttle manager was in favor of implementing the system.

However, since there will be no excess demands for secondary resources over the next 5–7 years, this process will not be used in the near future. The lack of demand for middeck lockers stems from the fact that near term Shuttle flights will be occupied by the International Space Station tools and hardware spares. However, this new demand has prompted the Space Station Program Payloads Office to assess a modification of this market-based process for producing Station manifests. In addition to the International Space Station, the Jet Propulsion Laboratory’s LightSAR radar mapping mission, the Cassini mission to Saturn and the Mars’01 Lander are currently evaluating a variant of our market-based system for generating conflict-free observation timelines.

Appendix A: Individual payoff sheets

Case 1: Each period consisted of 2 Shuttle flights to be packed and each period was a replication (values and resources) of the previous period.

Resources per period.

Shuttle flight 1			Shuttle flight 2		
Lockers	Watts	Crew	Lockers	Watts	Crew
5	2000	48	5	2500	47

Individual payoffs per period.

Participant 1

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
A	1	100	20	310
B	1	100	15	200
C	1	75	10	140
D	1	40	5	50
E	1	40	2	20

Participant 2

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
A	1	100	15	205
B	1	75	12	190
C	1	75	10	120
D	1	50	5	85
E	1	30	1	25

Participant 3

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
A	1	100	20	250
B	1	100	15	235
C	1	75	10	125
D	1	40	5	85
E	1	40	2	20

Participant 4

Budget—100—points every 2 flights Conversion Rate—

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
A	1	100	15	205
B	1	75	12	190
C	1	75	10	120
D	1	50	5	85
E	1	30	1	25

Participant 5

Budget—100—points every 2 flights Conversion Rate—

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
A	1	100	20	250
B	1	100	15	235
C	1	75	10	125
D	1	40	5	85
E	1	40	2	20

Case 2: Each period consisted of 2 Shuttle flights to be packed and each period was a replication (values and resources) of the previous period.

Resources per period.

Shuttle flight 1			Shuttle flight 2		
Lockers	Watts	Crew	Lockers	Watts	Crew
4	600	35	4	1000	45

Individual payoffs per period.

Participant 1

Budget—100—points every 2 flights Conversion Rate—

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
1A	2	300	15	100
1B	1	100	10	35
1C	1	200	5	30
1D	1	50	1	10

Participant 2

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
2A	1	400	15	100
2B	1	100	10	30
2C	1	200	5	35
2D	1	50	5	10

Participant 3

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
3A	1	300	15	100
3B	1	200	10	35
3C	1	100	5	30
3D	1	50	1	10

Participant 4

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
4A	2	300	20	85
4B	1	100	10	50
4C	1	200	5	50
4D	1	50	5	10

Participant 5

Budget__100__points every 2 flights Conversion Rate__

Payload value sheet

Payload	Lockers	Watts	Crew-time	Value
5A	2	400	15	85
5B	1	200	10	60
5C	1	100	5	40
5D	1	50	1	10

Simulation: Each period consisted of 6 Shuttle flights to be packed and each period was a replication (values and resources) of the previous period.

Resources per period.

	Flight 1	Flight 2	Flight 3	Flight 4	Flight 5	Flight 6
Lockers	9	8	13	8.5	8	13
Watt-hr	368	567	697	665	329	960
Crew hr	56.5	32.25	40.5	19.5	27	8.25

Individual payoffs per period.

Name	Lockers	Watt hours	Crew time	Value
Code U payloads				
MGBX-01	6	237	56	123
CGBA-04	4	136	5.166	40
PARE/NIH-R-03	3	67	10.91	37
CPCG-07	1	128	5.833	30
CPCG-08	1	128	2	25
PCG-STES-04	1.5	128	13.66	25
PCG-TES-02	3	115	0	21
CPCG-09	1	128	0.5	21
CPCG-08	1	128	0	20
PARE/NIH-R-02	2	57	3.266	20
PCG-STES-01	1.5	128	0	18
PCG-TES-03	3	115	0	15
CHROMEX-05	1.5	81	0	15
PARE/NIH-R-01	2	57	0	12
PCG-STES-03	1.5	128	0	10
PARE/NIH-R-04	2	57	6.166	10
BRIC-07	1	0	0	9
BRIC-08	1	0	0	9
BRIC-09	1	0	0	9
BRIC-04	1	0	0	8
BRIC-05	1	0	0	8
CGBA-03	2	30	3.583	7
BRIC-01	1	0	0	6
BRIC-06	1	0	0.583	5
DoD payloads				
STL-A/NIH-C-04	1	28	1.833	20
STL-B-01	1	103	3.583	16
STL-A/NIH-C-02	1	28	0	15
STL-A/NIH-C-05	1	26	3.5	15
MSX-03	0	30	5	15

(*Continued on next page.*)

(*Continued*.)

Name	Lockers	Watt hours	Crew time	Value
MSX-05	0	30	5	15
MSX-01	0	30	2	10
CREAM	1	3	0	5
RME	0.3	0	0.433	3
Code F payloads				
SAREX-B	0.5	100	6.666	40
SAREX-C	0	100	6.916	40
SAREX-A	0.5	100	0	30
XERAS-A	1	50	5	20
XERAS-B	0.5	100	6	15
XERAS-C	0.5	50	7	13
Code S payloads				
HERCUULES-03	3	130	22.16	55
EPICS	2	231	1.333	50
VIEW-CPL	1.5	181	28.41	50
HERCULES-01	2	150	15	45
HERCULES-02	3	100	20	39
WINDEX-02	1	30	14.41	30
Code X payloads				
MACE-01	4	450	0	70
MACE-04	3	400	10	59
MACE-05	4	300	0	57
MACE-03	2	300	0	50

Notes

1. We suspect that anyone who has an account on a shared computer network has been sent a message from the system administrator requesting them to eliminate unwanted files because the harddisk is filling-up.
2. The request to develop a market-based approach for Shuttle Secondary Payloads was based on the success of a trading system developed for the Cassini Mission to Saturn (see Ledyard et al. (1994) and Wessen and Porter (1997) for details of that system).
3. In this paper we ignore the interaction between the payload design decisions and the demand for Shuttle flight resources. This is of course an important interaction but is not central to the problem we are addressing.
4. This is correlated with the budgets devoted to developing secondary payloads since a request must be for a payload that is funded and in development.
5. Two additional rules were imposed in our experiments to speed-up convergence. First, a maximum number of rounds (8) were permitted and new bids had to beat the current bids by 10%. In addition, the process would stop before round 8 if the allocation did not change.
6. The use of experiments in economics to test various theories of behavior has been standard fare for quite some time (see Smith, 1982; Plott, 1989; Kagel and Roth, 1995) for a review of this methodology).

7. The URL for this site is http://linus.econlab.arizona.edu/experiments. The interested reader is referred to the secondary payload market simulation that is available at this site. There is a simulation at that site where you can participate against a set of "smart" bidding robots.

References

Banks, J., Ledyard, J., and Porter, D. (1989). "Allocating Uncertain and Unresponsive Resources: An Experimental Approach." *Rand Journal of Economics*. 1–25.

Clearwater, S., Costanza, R., and Schroeder, B. (1995). "Commodity Thermal Markets in Building Energy Management." *Energy Engineering*. 92(3), 6–22.

Kagel, J. and Roth, A. (1995). *The Handbook of Experimental Economics*. Princeton University Press.

Ledyard, J. (1993). "The Design of Coordination Mechanisms and Organizational Computing." *Journal of Organizational Computing*. 1, 121–134.

Ledyard, J., Rangel, A., and Porter, D. (1994). "Using Computerized Exchange Systems to Solve An Allocation Problem in Project Management." *Journal of Organizational Computing*. 4(3), 271–296.

McAfee, P. and McMillian, J. (1996). "Analyzing the Airwaves Auction." *Journal of Economic Perspectives*. 10, 159–175.

Milgrom, P. (1998). *Auction Theory for Privatization*. Cambridge University Press.

Olson, M. (1993). "Dominant and Nash Strategy Mechanisms with Transfers in the Assignment Problem." TRACE Discussion Paper 93-17, Tinbergan Institute, Amsterdam-Rotterdam.

Plott, C. (1989). "An Updated Review of Industrial Organization: Applications of Experimental Economics." In R. Schmalensee and R. Willig (eds.), *Handbook of Industrial Organization*.

Plott, C. (1994). "Market Architectures, Institutional Landscapes and Testbed Experiments." *Economic Theory*. 4(1), 3–10.

Rassenti, S., Smith, V., and Bulfin, R. (1982). "A Combinatorial Mechanism for Airport Time Slot Allocation." *Bell Journal of Economics*. 13, 402–417.

Smith, V. (1982). "Microeconomic Systems as An Experimental Science." *American Economic Review*. 72, 923–955.

Wessen, R. and Porter, D. (1997). "A Management Approach for Allocating Instrument Development Resources." *Space Policy*. 13(3), 191–201.

Wohl, A. (1997). "The Feasibility of An Index-Contingent Trading Mechanism." *Management Science*. 43(1), 112–121.