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Using Computerized Exchange Systems to Solve an Allocation Problem in Project Management

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In this article we study the allocation problem facing the management of a large research and development project. The project management has to allocate resources among competing users to achieve the project goal. Besides the constraint of scarcity, the allocation problem is difficult because users have private parameters that project management requires to know in order to make an optimal allocation. Furthermore, users have incentives to misrepresent the information about these parameters to advance their individual agendas, which can differ from the project goal. A method to solve the allocation problem using computerized exchange institutions is introduced and analyzed. We emphasize that the rules of the exchange should be carefully selected, because different rules produce different results. We use the methodology of experimental economics to demonstrate this conclusion. This research was motivated by JPL's Cassini Mission to Saturn. A computerized exchange described in this article has been implemented by the Cassini Project to assist in the management of the resources used in the design and operation of science instruments.

computerized exchange, experimental economics, project management,
group decision support systems

1. INTRODUCTION

The National Aeronautics and Space Administration's (NASA's) Cassini Mission to Saturn is a space science mission managed by the Jet Propulsion Laboratory (JPL) of NASA. The goal of the mission is to launch an instrumented spacecraft

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to orbit Saturn and deliver a probe to Titan, a moon of Saturn. Although the fulfillment of such a goal constitutes a serious technical challenge, the management decisions facing the Cassini project manager are also complex.

Project management has to supervise the construction of 13 science instruments and a probe. These instruments make scientific measurements in deep space to fulfill the goal of the mission. The collection of science instruments is diverse: for example, the Imaging Science Subsystem will perform multispectral imaging of Saturn and the Cosmic Dust Analyzer will, as its name indicates, analyze interstellar dust. The science teams developing these instruments are located in five different countries: the USA, the UK, Italy, France, and Germany. Project management has to allocate a vector of resources to each investigation team. These resources will be used to build and operate the science instruments. Currently, the vector of resources has sixteen dimensions: funding in seven different fiscal years, three data transmission operational modes, five operational power modes, and mass.¹

The allocation of resources to the different investigation teams is an especially complicated problem, because the project manager does not have all the information required to successfully distribute the resources. Each science team knows parameters that are relevant to the allocation process, but they are only known by members of that team. A naive management approach would be to simply ask each team for the value of those parameters and then solve the overall problem centrally. But the project manager cannot rely on an allocation process that requires the solicitation of each instrument team's private parameters, because the teams have an incentive to misrepresent their information.

In the next section we define in more detail this allocation problem and a proposed solution. The approach we have taken is the design and implementation of a computerized exchange institution: a type of decision support system. But deciding to implement a decision-support system—or a computerized exchange—is not the only decision facing the project manager. In Sections 3 and 4 we show that different versions of these decision systems can produce different results. So, care must be taken to select the better design. Furthermore, if some features of the environment are known, the computerized system can be tailored to the specific environment. We make use of a methodology developed by experimental economists during the past 20 years to provide guidance in the design and proof of concept in the implementation.

Based on the studies described in this article, we have developed a group decision support system, called the Cassini resource exchange (CRE), which the Cassini project management is now using in its allocation process. In Section 5 we give more details about this field implementation of CRE. We conclude the article by discussing some open research questions.

¹Part of the management problem involves identifying and defining these resources. We do not discuss that step in this article.

2. A DESCRIPTION OF THE ALLOCATION PROBLEM

The allocation problem facing the project management of the Cassini Mission can be conceptualized as follows:

- i. There are $n + 1$ agents in the mission. The first n agents are *instrument teams*. The last agent is the *project management*. The job of the instrument teams is to design and build science instruments that will make measurements in deep space. The project management is responsible for the successful completion of the mission. The responsibilities of the project management include many different tasks, but we are going to concentrate on the allocation of scarce design resources to the instrument teams.
- ii. The goal of the mission is to build the science instruments that will be mounted on a spacecraft and sent to space to make scientific measurements. Each science instrument performs a particular task in support of the mission and is built by a different instrument team.
- iii. Each investigation team needs to be allocated a vector of resources to build and operate their science instrument. The needs of each team differ significantly.
- iv. We treat the spacecraft design as exogenous.² It provides a fixed amount of resources to the project management for instrument development³. We can represent the total resources available for instrument development as a vector in m -dimensional-Euclidean space denoted by $tot = (tot_1, \dots, tot_m)$, where tot_i denotes the total amount of the i th-commodity available for instrument development.
- v. The problem facing the project management is the allocation of tot to each instrument scientist. We denote by $x_i = (x_{1i}, \dots, x_{mi})$ the vector that describes an assignment of resources to the i th scientist. A feasible allocation, $x = (x_1, \dots, x_n)$ with $x_1 + \dots + x_n = tot$, is a vector specifying an assignment of resources to every instrument team. This definition of an allocation assumes that the project management assigns all the resources available for science to the instrument teams.
- vi. The quality of any instrument is a monotonically increasing function of the amount of resources assigned to the instrument. As a result, an instrument team can always improve the quality of its instrument if given more resources.

²The selection of a spacecraft design and its successful construction and operation is one of the most difficult problems facing project management. However, we will only concentrate on the management of the science instrument allocations.

³In the introduction we mentioned funding as one of the resources. Cassini operates under a fixed-price contract, and, as a result, the amount of funding available for science instrument development and operation is also fixed.

- vii. Instrument teams care mostly about the quality of their own instrument; they always prefer more resources to less. Thus, if the project manager has an extra amount of any commodity to allocate, every team wants to have it.

Conditions (i)–(vii) describe the general characteristics of the allocation problem, but there are other features that make the problem really difficult. An important aspect of the problem is that the project management does not know how allocations map into mission performance. If there were a “quality function,” call it F , the problem of the project management would simply be:

$$\begin{array}{ll} \max & F(x_1, \dots, x_n) \\ x_1, \dots, x_n & \\ \text{s.t.} & x_1 + \dots + x_n = \text{tot.} \end{array}$$

The “quality function” is not known to project management because there are informational asymmetries among the project participants. The relevant information that the project management needs to generate a quality index for the mission is not the assignment to every instrument team but the quality of the instruments that the teams will produce using such assignments.

We assume for every instrument team there exists a function that maps x_i into a quality index for the instrument, denoted by Q_i . This function captures the costs and trade-offs inherent in the instrument development process. In practice, the team may not know its own function (that is why it does research and development—R&D), but it does know more than project management. If management can get the teams to provide accurate and timely information about this quality function, then management can come closer to generating that combination of instruments that maximizes the quality of the mission.

Even if a mission quality function does not exist, some allocations should be avoided. To see why, we need a concept of efficiency. An allocation x is said to be *inefficient* if there exists an allocation y such that the quality of every instrument under y is at least as good as the quality of every instrument under x and there is an instrument team whose instrument has a strictly higher quality index under the y allocation. An allocation that is not inefficient is said to be *efficient*. If we assume that the quality index of the mission increases as the quality of any instrument increases, the project management should avoid inefficient allocations, because at an inefficient allocation the quality of the mission could be increased without using more resources.

An example is given by the following parameters. Suppose that there are two instrument teams and that only two commodities are used in the process of instrument development. Let $\text{tot} = (10 \text{ watts}, 10 \text{ kg})$, $Q_1 = 10x_{11} + x_{21}$, and $Q_2 = x_{12} + 10x_{22}$. Is the allocation $x = (5,5), (5,5)$ efficient? No, because under the allocation $y = (10,0), (0,10)$ both teams can construct a strictly better instrument. In fact, the allocation y is efficient.

The following example illustrates that, given the informational asymmetries

and the preferences of the instrument teams, each team has an incentive to misrepresent their quality function if asked by the project management. Suppose that the project management wants to implement an allocation that is efficient and produces balanced science. Balanced science means that all the instruments have approximately the same quality. This assumes that the quality indexes allow for comparability across instruments. Given the parameters described above, project management wants to implement the allocation $w = ((10,0), (0,10))$ in which quality is balanced at 100 units. In particular, this is the maximum quality value per instrument for balanced science. But notice that if team 1 can lead the project manager to think that Q_1 is given by $2x_{11} + x_{21}$, she will implement the allocation $u = ((10,80/11), (0,30/11))$. That clearly favors the first team. The incentives to misrepresent are equally strong for the other team.

We call the problem of implementing an efficient allocation of resources the *allocation problem*. The task of the project management in this environment is to solve the allocation problem. The management could conceivably learn the shape of every instrument quality function if enough effort is put into learning and monitoring. However, this management approach requires large amounts of resources devoted to solving the allocation problem. The vector *tot* of commodities available for instrument development is equal to the total amount of resources available in the project minus the resources spent in solving the allocation problem. If the project management spends a significant amount of resources in monitoring the science teams, she could reduce the *tot* vector so much that little would be left for the actual development of the science instruments. We define the *organizational problem* as the problem of solving the allocation problem using a methodology that minimizes the amount of resources devoted to coordination.

One possible way to attack the organizational problem uses the principle of *voluntary trading*. This principle states that two agents exchange resources only if they are better off after the exchange. Note that agents can find a mutually beneficial exchange of resources only if they are at an inefficient allocation, because otherwise they would not be able to find a reallocation of resources that complies with the principle of voluntary trading. If the process of finding a mutually beneficial exchange is not difficult, the agents could execute a sequence of trades that converges to an efficient allocation. This would solve the allocation problem. If the implementation and operation of the voluntary exchange process is not too expensive, this would be an adequate solution to the organizational problem.

A very important feature of the process of voluntary trading is that the project management does not need any information about the quality functions for the instruments; information is decentralized in a very natural way because every team only needs to know its own parameters. Under this methodology the job of the project management is to give an initial allocation to the group and then to facilitate the process of voluntary trading. Regardless of the criteria used by the management in the initial allocation process, its impact on the efficiency of the system is softened by the process of voluntary trading. Furthermore, the

project management can be sure that the scientists will attempt to find a sequence of trades that converges to an efficient allocation, because it is in their individual interests to execute such trades.

3. IMPLEMENTING AN EXCHANGE SYSTEM

The decision to implement an exchange system to solve the organizational problem does not guarantee a solution. Because different exchange systems may produce different results at different costs, the project management has to implement a trading system that increases the efficiency of the system net of transaction costs.

This section discusses alternative implementations of an exchange system and their comparative advantages and problems. We look at three possibilities: trading by phone, the project management as a central broker, and computerized exchanges.

3.1 Method 1: Trading by Phone

The simplest exchange organization that the project manager could provide is a laissez-faire system. Under this organization, the management notifies the teams that they are free to trade among themselves and that the only constraint is that they must notify the project manager of their trading decisions in order to keep the accounting up-to-date.

An instrument team that wants to trade has to find a trading partner. The method and resources spent in finding trading partners are left open to the agent. Using the phone (or an alternative communication device such as electronic mail or fax) is a plausible alternative, especially if the prospective trading partner is in a different country and meetings are hard to arrange.

The task of trading depends on the difficulty of solving the *problem of finding a coincidence of wants*. Let $b_i \in \text{tot}$ be a vector describing the trade that the i th team wants to perform; we call b_i a *bid*. The positive components of the bid denote what the instrument team wants to receive in the trade and the negative components what they are willing to give up in exchange. A bilateral trade is a trade in which two agents, i and j , exchange resources. The problem of finding a coincidence of wants for i is to find an agent j that wants to trade b_j , such that $b_i + b_j = 0$. That is, in order to trade, i needs to find a trading partner with exactly the opposite wants.

If the number of tradable commodities in the project is large, the likelihood of finding another agent with exactly the opposite wants may be small. In order to complete a desired trade, the i th agent may have to perform a long sequence of intermediate trades so that, after the last trade in the sequence is executed, the agent has finally changed her allocation by the amounts desired. For example, assume the problem involves three instrument teams and three commodities. Suppose the trades the teams want to execute are $b_1 = (-10, 0, 10)$, $b_2 = (10, -10, 0)$ and $b_3 = (0, 10, -10)$. If the first team tries to trade with the second team, they will

both realize that they do not have a coincidence of wants because $b_1 + b_2 \neq 0$. The same thing happens if teams one and three try to trade. However, if the first team notices that if they first trade $-b_3$ with the third team and then $-b_2$ with the second team, they will end up at their desired allocation.

In solving the problem created by a lack of coincidence of wants this institution requires a lot of phone calls, sharpness, computational skills, and most important, the willingness to temporarily hold an undesired allocation. In more realistic cases, the demands that this institution imposes on the instrument scientists can make transaction costs prohibitive. If finding desirable trades is too expensive, individuals will not trade, because all the gains from exchange are offset by the high transaction costs.

3.2 Method 2: Project Management as a Central Broker

The example above shows that trading by phone might not solve the organizational problem, because finding a coincidence of wants might be too difficult or expensive. Perhaps if the project manager acts as a central broker the amount of resources devoted to finding a coincidence of wants could be reduced. In the centralized institution, agents report their bids to the project manager, who tries to solve the problem of finding a coincidence of wants; in principle, at least the communication costs are reduced, because this system requires a smaller number of messages.

Although agents express their willingness to trade through a particular bid, there are many trades that would make an agent better off. When an agent sends a bid to the broker it does not mean that this is the only bid that the agent is willing to make. In particular, the agent needs to see the bids of the other individuals to judge if any of these bids constitutes an acceptable trade. As a result, if the project management wants to act as a central broker, many computations and much communication is required. The teams will have to provide many bids to the project. The broker will have to call the agents every time a new bid comes in to see if others are interested in trading. Regular meetings may have to be scheduled often for negotiation to take place. It is easy to see that this methodology can have large transaction costs. If the project manager wants to do an adequate job as a central broker she may have to execute an enormous amount of computation and send many messages. These informational and computation constraints could be loosened if the process is decentralized and computerized.

3.3 Method 3: A DSS Approach

The institution for choosing a computerized institution is based on the fact that we can use the power of modern computers to reduce the costs of coordination. The cost reductions occur because, if properly implemented, the computerized market can facilitate the process of finding a coincidence of wants and reduce communication costs. In the next three subsections we present three alternative computerized institutions and discuss their comparative advantages.

3.3.1 Bulletin Board: A Barter Exchange

A simple computerized market is a bulletin board (BB) that allows individuals to signal a desire to trade by placing bids where everybody can see them. With a BB, agents can look at other individuals' bids to see if one is acceptable. This institution provides a good solution to some of the problems described above, because the flow of messages in the system is clear. Every agent sends and receives messages directly from the computer; agents need access the system only if they have an interest in trading.

Although a bulletin board provides a good and inexpensive medium for communication, not all the coordination problems have been resolved. Let b_1, \dots, b_n be the proposed trades in the system by agents 1 to n respectively. As defined above, there exists a bilateral coincidence of wants between agents i and j in the system if $b_i + b_j = 0$. We say that there exists a t -person chain or a t -person multilateral coincidence of wants if there are t agents, call them w_1 to w_t , such that $b_{w_1} + \dots + b_{w_t} = 0$ and a similar condition does not hold for a subset of the t agents. Note that a chain can be visualized as a reallocation of resources in which each agent trades her desired bid, but it is not possible that such a reallocation can be executed for a subset of the t agents.

In the example above, where $b_1 = (-10, 0, 10)$, $b_2 = (10, -10, 0)$ and $b_3 = (0, 10, -10)$, we see that the three teams have a three-person chain because $b_1 + b_2 + b_3 = 0$, $b_1 + b_2 \neq 0$, $b_1 + b_3 \neq 0$ and $b_2 + b_3 \neq 0$. The example also illustrates that even if only bilateral trades are allowed in the system, the reallocation of resources described by the chain can be executed if an agent performs the necessary sequence of bilateral trades. But the completion of chains using a sequence of bilateral trades creates the following problems:

- If the number of tradable commodities is large, the problem of finding chains and their required sequence of bilateral trades is a combinatorial problem. Further, the difficulty of the problem increases significantly if agents are allowed to place more than one bid.
- It takes time to complete the sequence of trades, and only at the last trade is the agent able to reach her desired allocation. Since, in the process of completing the sequence of trades, one of the other agents might change her mind, the agent completing the sequence bears the risk of ending at an undesired allocation.

3.3.2 Medium of Exchange: Use of a Numeraire Good

Every day millions of transactions take place in the world among millions of agents. These trades use money as a bilateral accounting device to solve the coordination problem. Instead of bartering, people buy and sell resources in exchange for an amount of money. And agents do not have to worry about finding a coincidence of wants. Since this methodology works well in the economy, it is reasonable to suggest the use of bilateral accounting devices in our computerized institution as a possible solution to the problems that simple barter presents. In order to describe what can be used as a bilateral accounting device

in our computerized exchanges, it is important to notice that money is not one of the consumption commodities in the economy. In the Cassini Mission environment, the agents have consumption value for all the tradable commodities in the exchange. So, if we want to have something analogous to money, we have to introduce tokens or fiat money.

The use of tokens or fiat money, however, in our environment presents major problems. In the economy, money is widely accepted as a medium of exchange because the exchange process continues ad infinitum. If the end of the exchange process were known, money would lose its properties as a coordination device. Because money has no consumption value on the last day of the exchange process, no agent would want to hold money. But this means that at the last day becomes closer, agents would have trouble getting commodities exchanged for money and the exchange process would stop. For a theoretical and experimental examination of this phenomenon see [1]. For the Cassini Mission the date of the closure of the market is known, and as a result, money loses its ability to coordinate.

A slight variation from the use of money can be introduced to solve the coordination problem without using fiat moneys. In this technique one of the commodities, called the *numeraire*, is selected as an accounting device and all the proposed trades are listed in terms of the numeraire commodity. Hence, combinations of goods are exchanged for an amount of the numeraire commodity. The numeraire institution has two important features:

- This computerized institution is a slight variation of the BB. Every trade in the numeraire exchange can be executed on the BB, since the BB is a barter exchange.
- Every trade in the numeraire mechanism must involve a transaction of the numeraire commodity. For example, suppose that there are three commodities: A, B, and C and that C is selected as the numeraire good. In the BB it was possible for two agents to trade A and B even if they did not own any amount of the numeraire good. In the numeraire system, such trades are not possible.

By reducing the message space (the set of possible trades in numeraire is a subset of the set of possible trades in the BB) and forcing agents to focus on the numeraire dimension this methodology provides some coordination. But the fact that not all the agents have the same preferences over the numeraire commodity can cause undesirable implications. Suppose, for example, in a three-commodity environment that a team does not use C, the numeraire commodity, in the construction of their instrument. In order to change their allocation in A and B, resources that are valuable to the team, they must first acquire some numeraire. This, however, requires the team to give up A or B in exchange for C, a commodity for which the team has no use. Having to temporarily hold an allocation of no use can cause uncertainty and may deter some agents from trading.

3.3.3 A Computer Assisted Resource Exchange (CARE)

The computational capabilities of modern computers can be utilized, using appropriate algorithms, to solve the coordination problems described above. All the methods suggested so far have one characteristic in common: they require the agents to perform a large amount of communication and computation. In some cases, for example, when trading by phone, agents have to send many messages. In others, for example, when using the BB, agents have to perform many computations to find a coincidence of wants. If the number of agents in the exchange is large, even the process of browsing through the list of bids on the BB can be a demanding task. If trading is hard or takes too long, the optimal strategy would be not to waste time trying to trade because implementing an efficient allocation would not be worth the effort. In that case, the implementation of an exchange institution would not be helpful.

CARE (an acronym for computerized assisted resource exchange) is a variation of the BB that executes the following tasks in order to assist the agents in solving the coordination problem:

- CARE can compute the chains in the system. It can also allow for the execution of chains without having to go through the full sequence of trades. If there are m agents in the system placing n bids each, the minimum number of computations required to find all the chains is (for $n \geq 2$):

$$\sum_{k=2}^n \frac{n! (2^m - 1)^k}{(n - k)! k!}$$

- If an agent cannot find a desirable trade with the bids that she has in the system, CARE offers information about how to modify the agent's bids to be able to complete a trade.
- If an agent is interested in trading only in particular subset of the commodities, CARE allows the user to filter out any undesired information and concentrate on the relevant dimensions.

Appendix A contains some screens from the CARE program used for the Cassini Resource Exchange. These screens provide an overview of the user interface.

4. PROVIDING PROOF OF CONCEPT

4.1 Experimental Economics: A Method for Testing Trading Systems

In the previous sections we have offered and discussed several different approaches to the implementation of a computerized resource exchange. However, it would be desirable to have some evidence to compare the performance of the alternative institutions. Providing such proof of concept is especially important when there is no operational history of the institution in question. In

aeronautical engineering this problem is solved by evaluating airfoils in a wind tunnel. We use a similar methodology for analyzing the properties of alternative barter designs.

Laboratory methods for the study of economic phenomena have been developed and refined over the past 30 years. Use of these techniques allows a detailed analysis of exchange institutions (see [2] and [3] for an overview of the literature in experimental economics and [4] for a discussion about the applicability of experimental economics as a tool to compare alternative allocation mechanisms).

The basic procedure is to conduct controlled experiments in which live subjects act as decision makers. For the allocation problem in which we are interested, each subject is provided with a detailed description of their instrument's quality function, their endowment, and the rules of exchange. The key parameters in the experiments are the values that participants place on the resources being exchanged. These preferences are induced over the exchange opportunities using monetary payoffs (see [5]) related to the decisions made by the subjects. If the subjects can improve the value of their quality function by exchanging resources with other subjects, they receive a higher monetary payoff at the end of the experiment. As long as the rewards are salient, relative to the cost of participating in the experiment, control can be maintained.

To summarize, the use of experimental methods to evaluate the performance of different institutions allows a systematic study in a controlled environment. The experiments provide a source of experience and data about how the alternative institutions might perform.

4.2 An Experimental Examination of Three Computerized Exchanges

4.2.1 Experimental Design

In order to examine the problem of coincidence of wants, we need to create an environment in which bilateral trading has the potential to result in losses. The environment we have selected has the property that the market equilibrium requires that trade occurs in three-person chains. The environment consists of three tradable commodities. A subject is given a payoff in which one of the commodities has a {0,1} step function payoff and the other commodities have a payoff structure defined by a Cobb-Douglas function. Three types of payoffs over three commodities labeled as A, B, and C were constructed and are provided below.

Listed in the graphs are the initial endowments. The right-hand graph shows the level surfaces of the Cobb-Douglas function over B and C. The contours start from -\$2 in payoff and increase by \$1 for each new contour. The market clearing point is also listed in the graphs. Notice that these agents would like to exchange C for B. Trading for A using B or C can only make them worse off than they are at their initial endowment. Notice that these agents would like to exchange A for C. Trading for B can only make them worse off. Notice that these agents would like to exchange B for A. Trading C can only make them worse off. Each experiment consisted of six subjects who were recruited from the student

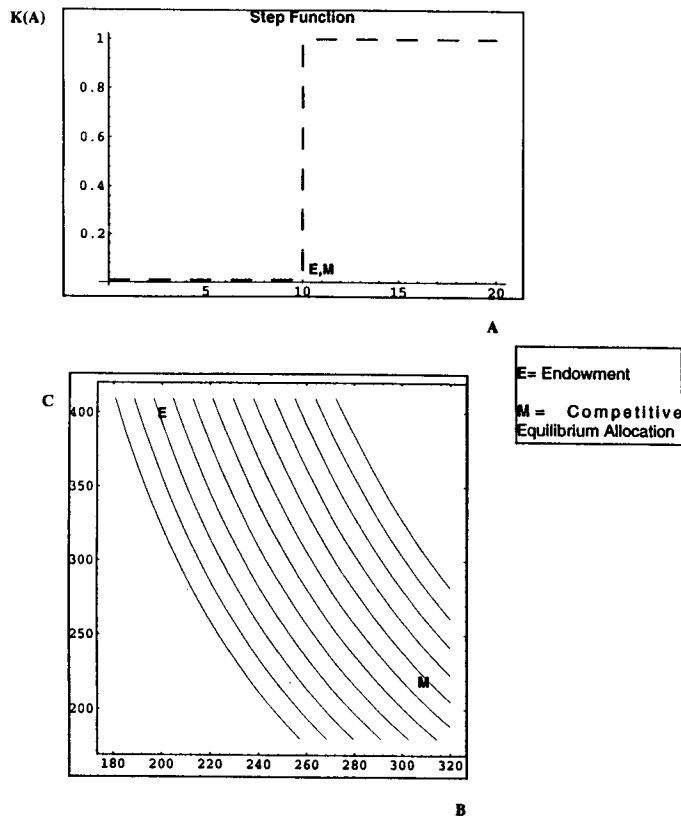


Figure 1. Type 1 payoffs: $K(A) (B^7C^3) - 245$.

population at the California Institute of Technology. Subjects one and four have type-one parameters; subjects two and five have type-two parameters and subjects three and six have type-three parameters. The earnings of the subjects are proportional to the value of their payoff function at the end of the experiment.

An experimental period starts with all the agents at their initial allocation and ends after twenty minutes of voluntary trading using the institution being tested. At the end of four experimental periods subjects were paid the sum of their earnings in every period plus a fixed fee for participating. We tested each institution with three different groups of people for a total of twelve experimental periods. The following results summarize what we learned in these experiments.

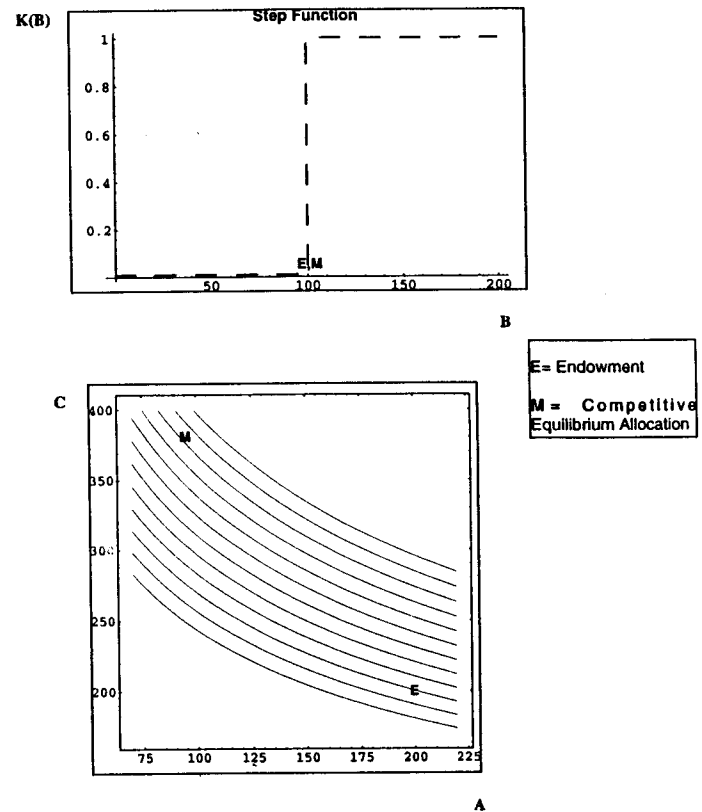


Figure 2. Type 2 payoffs: $K(B) (A^3C^7) - 245$.

4.2.2 Experimental Results

(1) In terms of their ability to reach an efficient allocation the three institutions can be ranked in the following decreasing order: CARE, Barter and Numeraire.

Figures 4 and 5 present two different measures of efficiency respectively. The measure presented in the first figure is called the *net gains from exchange* (NGFE).⁴ This measure defines, for a particular allocation, the percentage of the

⁴This measure utilizes the concept of the Coefficient of Resource Utilization developed by Gerard Debreu [6].

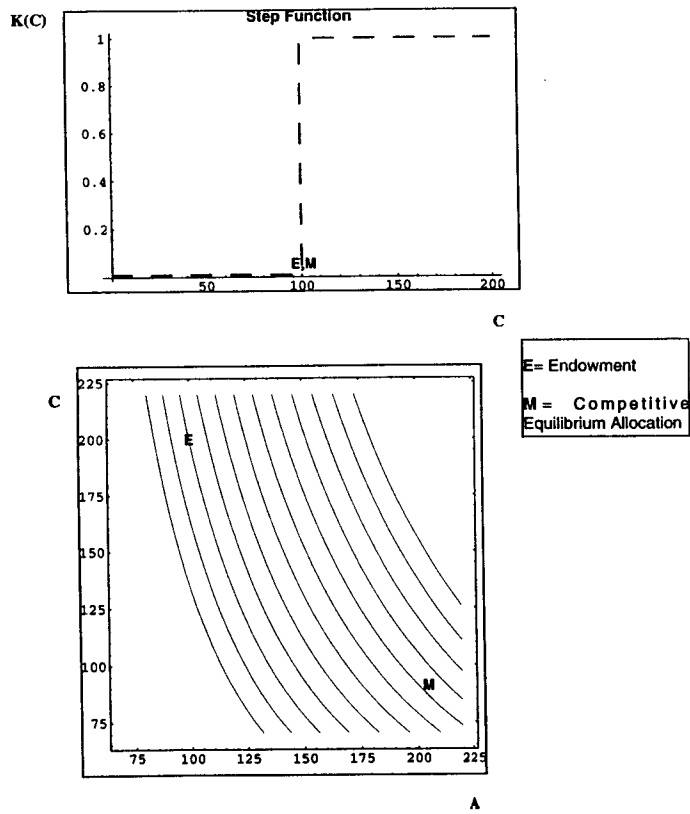


Figure 3. Type 3 payoffs: $K(C)$ (A.7B.3)—245.

gains from exchange that have been extracted. The metric is determined by weighting the initial allocation with its competitive equilibrium prices (CE) and subtracting it from the CE-weighted final allocation after trading. This amount is then normalized by the maximal possible increase from the initial allocation. A NGFE of 100% is achieved only at an efficient allocation.

Figure 5 reports a different measure of efficiency. At every final allocation we computed the Euclidean distance in the commodity space between the final allocation and an allocation that exhausts gains from exchange from the final allocation. If the final allocation is efficient, the value of the distance is zero; for inefficient allocations, the higher the distance the lower the percentage of

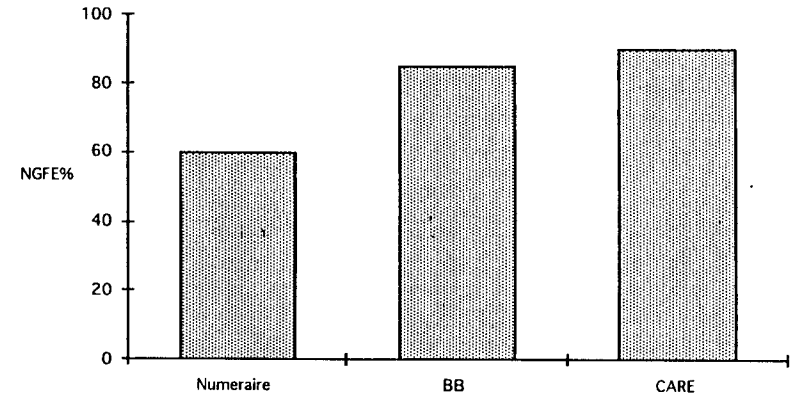


Figure 4. Average NGFE.

resources that are being "fully" utilized. The figures show the per-period average across groups for the three institutions.

In order to extract the gains from exchange, in BB and Numeraire the subjects have to carry out undesirable trades, because these mechanisms can execute only bilateral trades. CARE solves the problem with the execution of chains.

(2) In CARE more than 40% of the transactions are multilateral reallocations of resources.

Figure 6 illustrates the distribution of transactions in the CARE mechanism among chains and bilateral trades. In the figure, a type-1 chain is equivalent to a bilateral trade. All the other values in the horizontal axis denote chains.

Recall from the definition of the organizational problem that its solution required not only the implementation of an efficient allocation but low transaction costs. A measure of the value of the transaction costs is given by the number of contracts that were executed and the number of units that changed hands. Table 1 gives the average value of these parameters for the three institutions.

(3) CARE has the lowest transaction costs.

(4) In BB and Numeraire, many of the transactions diminished the payoff of the agents; but in CARE the distribution of changes in utility is almost entirely positive. Thus, CARE lowers transaction risks.

A measure of how difficult it is for the subjects to find and execute payoff-increasing trades is given in Figure 7. This figure contains the average changes in payoff per trade for all the mechanisms and periods. It also shows the 95% confidence intervals around the mean values.

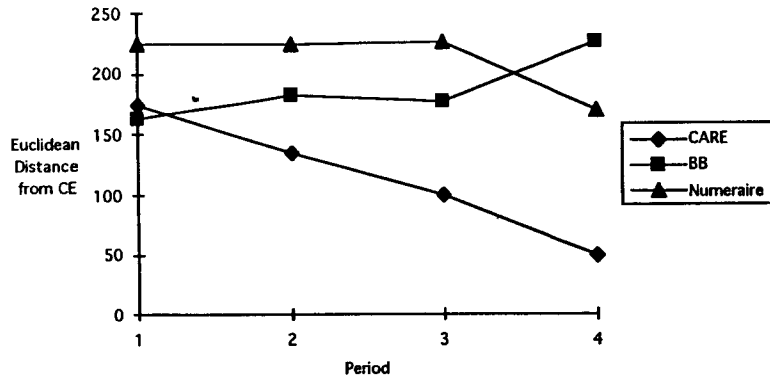


Figure 5. Average distance to the CE.

5. FIELD IMPLEMENTATION

A version of CARE is being implemented for the Cassini Mission under the name of Cassini Resource Exchange (CRE). The software resides on the Internet³ and is operated through the Division of the Humanities and Social Sciences at the California Institute of Technology. Every instrument scientist, including the overseas users, has an account for trading. The software requirements on the users are minimal; they only need access to an X-windows terminal connected to the Internet.

The allocations given to the science teams include funding and "physical resources" like mass, power, and data. The initial allocation determines a set of design parameters for the spacecraft. Examples of the parameters are: (1) center of gravity and moment of inertia related to the mass allocations and (2) thermal constraints related to the power consumption. Unlike the experimental testbed there exists an externality problem because when two instruments trade some of these spacecraft parameters may change. To deal with this on the Cassini Mission, an extra rule had to be added to the CARE mechanism. An engineer at the Jet Propulsion Laboratory must decide if the trade is acceptable and determine, if necessary, compensation for the affected agents.

The market opened on April 15, 1993. Trading has been infrequent, but there have been 18 contracts as of October 1, 1993. Only one contract was a chain. All of the bid and contract information is provided in Figure 8. The figures show buy orders, sell orders, and contract prices by weekly increments. The numbers above the contracts are the volume associated with each trade. For the money markets, the numbers are in thousands of dollars. Thus, during week 20 in the

³The Internet is an international computer network that is commonly used by the academic and scientific community.

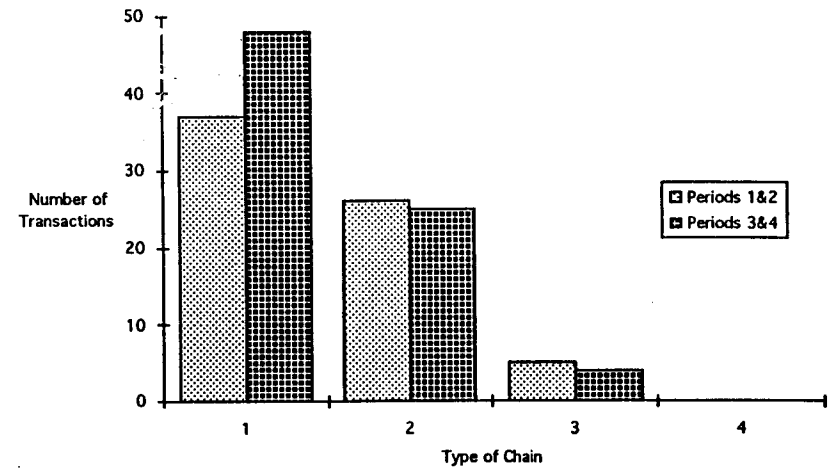


Figure 6. Types of transactions in CARE.

Table 1
Trading Statistics

INSTITUTION	# OF CONTRACTS PER PERIOD		AVERAGE VOLUME PER PERIOD			
	MEAN	STANDARD DEVIATION	A	B	C	TOTAL
CARE	12.1	3.67	241	337	401	979
BB	15.5	4.12	345	303	486	1134
Numeraire	22.8	8.59	229	246	644	1119

1993 funds for 1994 funds market, a trade was made at an interest rate of 5%, that is, \$700,000 of 1993 funds was offered in exchange for \$735,000 in 1994 funds. Notice that there is a clear premium for funds that are further away from the current year.

The mass market has had considerable activity, which has come mainly from an auction conducted by the spacecraft team during weeks 5-7 in which they sold 7 kg of mass for \$350,000. While the market has been operational and the science teams do frequently access the market, the tracking rate seems low. There are two major observations on the conduct of this market that might explain this. First, the ownership of resources has been clouded for both power and data rate. As you have probably already noticed, there have been no offers or trades made in the power and data-rate markets. This outcome seems due to

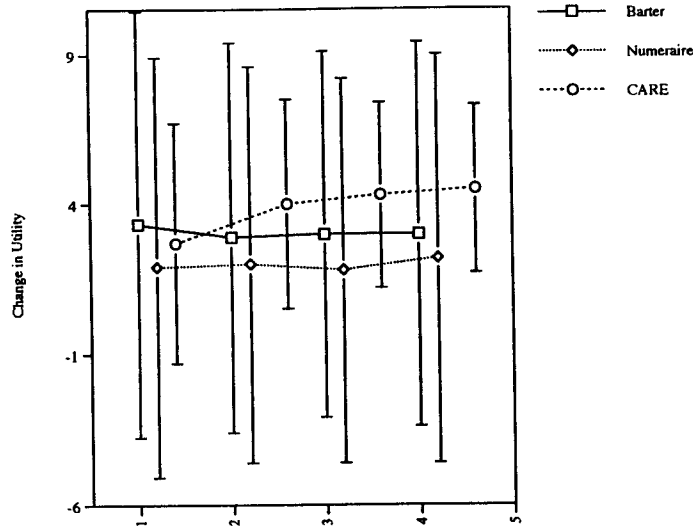


Figure 7. 95% confidence intervals of utility changes from trade.

the fact that these commodities are hard to define with any specificity and that the science manager is holding back resources for thermal control and "enhanced science." Although the intentions of the science manager are good, this uncertainty, in potential power and data-rate dividends that have not been specified, has dried up this market and is the probable reason why we have not seen trading in chains. Second, while the bulletin board is accessible, most of the offer and trade information has been "informal" with e-mail and calls to the bulletin board operator. The operator in turn has called or e-mailed parties who have shown interest. Whether this initial use of "brokering" is the result of market thinness or the "cultural" background of engineers remains to be seen as this market matures.

6. SOME OPEN QUESTIONS

This article discusses the use of computerized decision support systems to assist the project management of a space science mission in the task of managing science instruments. However, not all the problems facing the project management were addressed. In particular, the selection of the set of instruments to be included in the mission and the selection of the science teams to build such instruments is taken as given.

Although implementing a solution to the organizational problem is a desir-

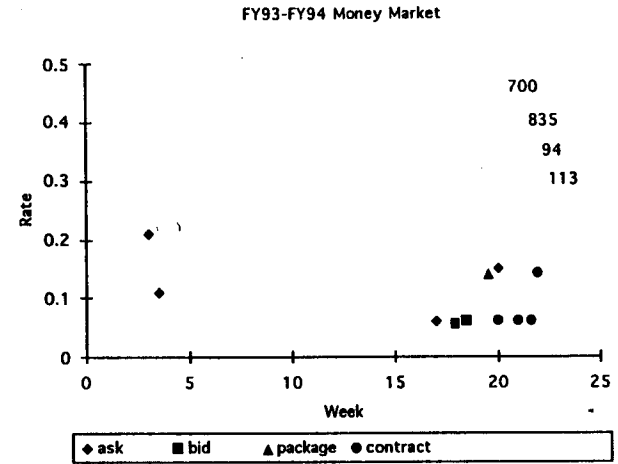


Figure 8a. Cassini exchange trading activity.

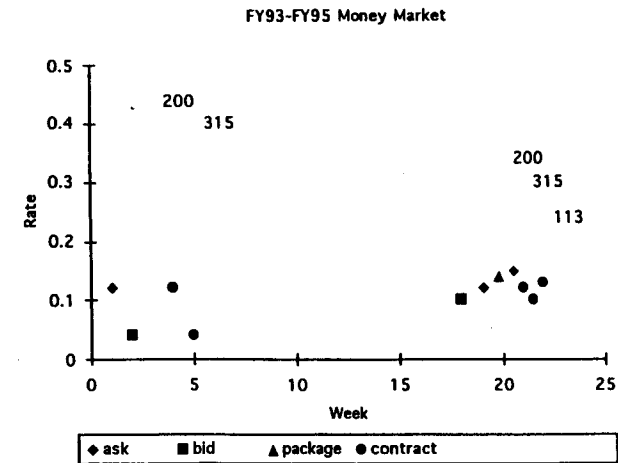


Figure 8b. Cassini exchange trading activity.

able goal for the project management, efficiency and low transaction costs are not sufficient conditions for a successful mission. Objectives like balanced science have to be addressed at the time of the initial allocation. The implementation of voluntary exchange mechanisms can soften the impact of the initial allo-

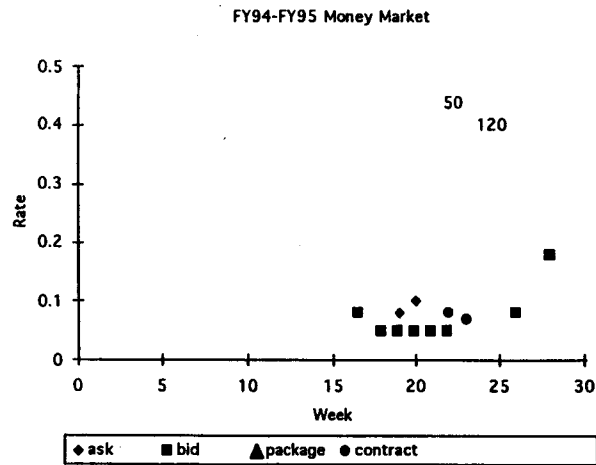


Figure 8c. Cassini exchange trading activity.

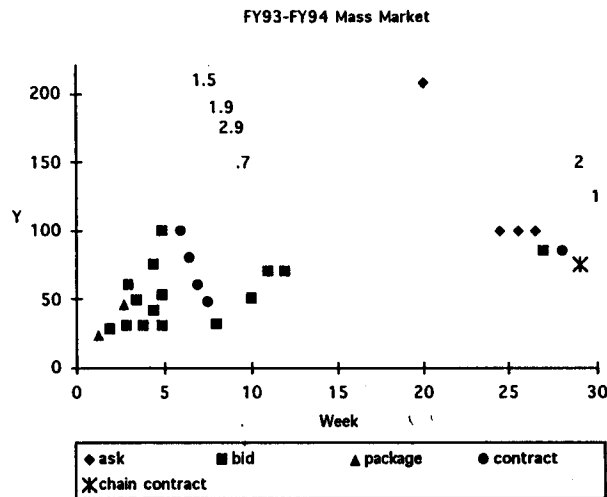


Figure 8d. Cassini exchange trading activity.

cation on the efficiency of the system, but they cannot correct poor initial allocations or solve a problem of severe scarcity of mission resources. How to make that initial allocation is a complex and difficult research question.

The space science mission scenario is not the only economic environment in which trading as an allocation policy could be useful. A number of different applications for the exchange institutions and the methodology described in this article have been suggested and are under consideration. These applications include:

- The trading of pollution permits;
- The swap of financial instruments;
- The resale of the electromagnetic spectrum;
- Transport networks; and
- Laboratory scheduling.

If the number of agents in the exchange is large, or if agents are allowed to place a large number of bids, and if the information needs to be updated continuously, the calculation of chains is a complicated combinatorial problem. The problem of exhaustively calculating all the chains in such an environment is NP-complete. The development of faster algorithms to compute chains becomes crucial if such computerized trading systems are to become practical on a large scale.

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APPENDIX A: COMPUTER SCREENS FROM THE CASSINI RESOURCE EXCHANGE

Trade

news options help

Warning: Cannot open shutdown file

assets bids history documents options

Name	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w	hp<s	h
umpire	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7
cirs	34.2	36.5	19.5	19.5	19.5	19.5	80.0	2
cda	16.1	6.5	22.5	19.5	10.0	10.0	20.0	1
rpws	26.7	18.3	15.3	18.3	3.3	3.3	27.3	1
caps	20.1	21.0	21.0	21.0	8.0	13.0	25.0	2
uvis	14.9	14.0	14.0	8.0	8.0	8.0	0.0	1
mimi	24.9	30.0	30.0	30.0	22.0	22.0	30.0	3
rss	13.2	0.0	0.0	0.0	0.0	55.0	0.0	3
iss	66.4	70.8	40.0	40.0	40.0	40.0	44.0	6
vims	40.0	28.5	3.0	3.0	3.0	3.0	128.0	3
inms	10.8	16.6	16.6	31.0	31.0	16.6	0.0	1
radar	56.5	0.0	0.0	0.0	120.0	0.0	0.0	1
gcms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
disr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
mag	8.7	12.0	12.0	12.0	5.0	12.0	12.0	1
scraft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
gds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1

assets bids history documents options

Bidder	B#	Con	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w
cirs	11	11*					-3.0	
cda	7	7	-1.0					
rpws	0	0	-1.0					1.0
mimi	3	3	-1.0	1.0				
mimi	4	3	-1.0					
iss	6	6	-1.0	1.5				
iss	7	7	-1.0					
iss	8	8	1.0					-1.0
iss	9	8	1.0					
mag	0	0	1.0	-2.0				
mag	1	0	1.0	-2.0				

Make A Bid

Make A Bid

mass 66.4	ors-w 70.8	dfpw-w 40.0	fpwi-w 40.0
-2.2			
radar-w 40.0	rss-w 40.0	hp<s 44.0	hp>s 65.0
ors 366.0	dfpw 0.0	fpwi 0.0	radar 0.0
rss 0.0	\$93 9010.0	\$94 10559.0	\$95 12600.0
		135	
\$96 4465.0	\$97 1554.0	\$98 216.0	

options erase note SAVE REPLACE help

	rpws	caps	uvis	mimi	rss	iss	vims	inms	radar	gcms	disr	mag	scraft	gds	hp<s	h
	26.7	18.3	15.3	18.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0	7
	20.1	21.0	21.0	21.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	80.0	2
	14.9	14.0	14.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	20.0	1
	24.9	30.0	30.0	30.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	27.3	1
	13.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	2
	66.4	70.8	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	30.0	3
	40.0	28.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	55.0	0
	10.8	16.6	16.6	31.0	31.0	16.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.0	6
	56.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	120.0	0.0	0.0	0.0	0.0	0.0	128.0	3
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	8.7	12.0	12.0	12.0	5.0	12.0	12.0	12.0	5.0	12.0	12.0	12.0	12.0	12.0	12.0	1
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1

assets bids history documents options

Bidder	B#	Con	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w
cirs	11	11*						
cda	7	7	-1.0				-3.0	
rpws	0	0	-1.0					1.0
mimi	3	3	-1.0	1.0				
mimi	4	3	-1.0					
iss	6	6	-1.0	1.5				
iss	7	7	-1.0					
iss	8	8	1.0					-1.0
iss	9	8	1.0					
mag	0	0	1.0	-2.0				
mag	1	0	1.0	-2.0				

Make A Bid

mass	66.4	ors-w	70.8	dfpw-w	40.0	fpwi-w	40.0
radar-w	40.0	rss-w	40.0	hp<s	44.0	hp>s	65.0
ors	366.0	dfpw	0.0	fpwi	0.0	radar	0.0
rss	0.0	\$93	9010.0	\$94	10559.0	\$95	12600.0
\$96	4465.0	\$97	1554.0	\$98	216.0		

hp<s h
0.0
80.0 7
20.0 2

options erase note SAVE REPLACE help

Make a new bid contingent on some exit

Pick	Info	Con	Id	mass	ors-w	dfpw	fpwi	radar	rss-w	hp<s	hp>s	ors	dfpw
			5	-1.0	1.5								
			7	-1.0									
			8	1.0								-1.0	
			9	1.0									
			10	-2.2									

Forward back CONTINUE quit help

assets bids history documents options

Bidder	B#	Con	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w
cirs	11	11*						
cda	7	7	-1.0	2.0		-3.0		
rpws	0	0	-1.0	2.0			1.0	
mimi	3	3	-1.0	1.0				
mimi	4	3	-1.0					
iss	6	6	-1.0	1.5				
iss	7	7	-1.0					
iss	8	8	1.0				-1.0	
iss	9	8	1.0					
iss	10	10	-2.2					
mag	0	0	1.0	-2.0				
mag	1	0	1.0	-2.0				

Pick A Bid Or A Chain

Pick A Chain

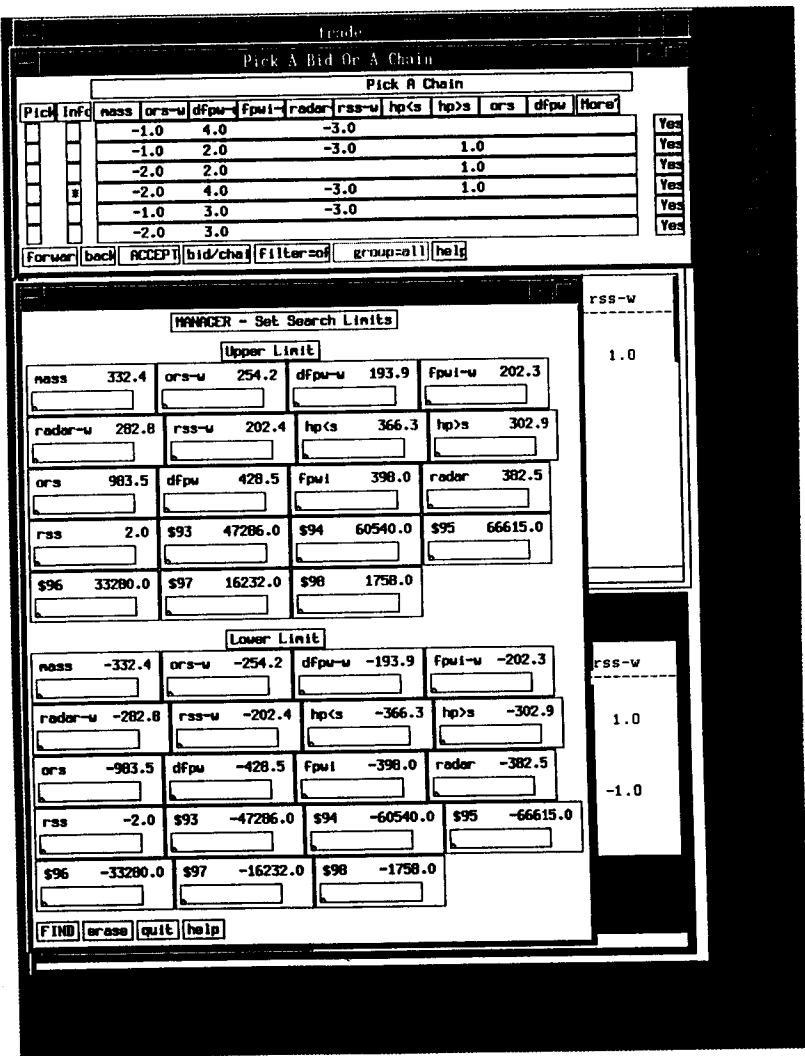
Pick	Info	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w	hp<s	hp>s	ors	dfpw	More
		-1.0	4.0			-3.0						Yes
		-1.0	2.0			-3.0			1.0			Yes
		-2.0	2.0						1.0			Yes
		-2.0	4.0			-3.0			1.0			Yes
		-1.0	3.0			-3.0						Yes
		-2.0	3.0									Yes

Forward back ACCEPT bid/chain Filterzof groupzall help

Bidder	B#	Con	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w
cirs	11	11*		2.0			-3.0	
cda	7	7	-1.0	2.0				
rpws	0	0	-1.0					1.0

assets bids history documents options

Bidder	B#	Con	mass	ors-w	dfpw-w	fpwi-w	radar-w	rss-w
cirs	11	11*		2.0			-3.0	
cda	7	7	-1.0	2.0				
rpws	0	0	-1.0					1.0
mimi	3	3	-1.0	1.0				
mimi	4	3	-1.0					
iss	6	6	-1.0	1.5				
iss	7	7	-1.0					
iss	8	8	1.0					-1.0
iss	9	8	1.0					
iss	10	10	-2.2					
mag	0	0	1.0	-2.0				
mag	1	0	1.0	-2.0				



On Integrating Collaboration and Decision Analysis Techniques

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We discuss how methods for computer-based collaboration and computer-aided decision analysis may be combined to yield a new generation of decision support systems. We examine the role of these technologies using a three-phase model (problem definition; problem structuring; modeling/analysis) of decision making activities. We argue that decision making is a recursive mesh of these three phases; i.e., each phase involves argumentation/discussion, structuring, and analysis. Representations and methods suited to one kind of activity (e.g., discussion) are not directly suited to the others. Decision support systems, therefore, should facilitate the use of all of these methods in a way that information represented under each of them may be combined effectively, supporting the decision makers in switching from one activity to another.

division support, collaborative work, systems integration

1. INTRODUCTION

Organizational decision making is a sociotechnical process that has several dimensions of complexity—it involves multiple issues, multiple criteria, and multiple stakeholders. It usually involves negotiation, discussion, evaluation, clarification, and analysis, all aimed at resolving underlying conflicts and uncertainties and at forming a shared understanding of problems and possible solutions. Developing such an understanding is particularly hard when there are multiple decisionmakers, and it usually follows from detailed argumentation and persuasion. The decision may be influenced by hard facts and formal meth-

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