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A SMART MARKET SOLUTION TO A CLASS OF BACK-HAUL TRANSPORTATION PROBLEMS: CONCEPT AND EXPERIMENTAL TESTBEDS

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A Smart Market Solution to a Class of Back-Haul Transportation Problems: Concept and Experimental Testbeds*

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Abstract: Back-haul problems occur in many areas of transportation. One way rental of equipment often takes it from an area of high demand to an area of low demand. Examples include container rentals, car rentals and other cases of mobile equipment. The problem is to return the equipment to the location of need. Typically this is viewed as an administrative and scheduling problem. The approach taken here is "decentralized" in which a specially designed market organizes competition and information to minimize the cost of back-hauls without the direct intervention of administrative negotiations or command-and-control types of scheduling. Laboratory experimental methods are employed to test the concept and explore its limitations.

Introduction

The *back-haul problem* is well known to management in many areas of transportation. The problem occurs when use of equipment involves its relocation, and it must be relocated again before it can be used again. Getting the equipment back to where it is needed is costly. For example, a customer who rents an international freight container or a moving truck may have the option to return it at a distant location. The owner may be able to rent it to another customer at its new location. However, if there is currently no demand at the return location, then the owner may need to back-haul rental units to a location where there is sufficient demand. Naturally occurring patterns of trade can create situations where back-haul is common.

When the owner of the rental units is also the owner of the least-cost transportation, the back-haul problem is merely one of optimization by a single agent. However, if the

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owner of the rental units must contract for the transportation from a number of providers, how can the owner attempt to attain a least cost outcome? Classically the problem is considered from the point of view of uncertainties and the complexities of scheduling. Here we add the complexity of asymmetric information in the sense that costs are known only to those hired to undertake the movements. Classically the problem is considered from the point of view of a single decision maker who formulates the problem on the best information available and makes a decision. By contrast this paper outlines a process for making such decisions and the heart of the process is a new, decentralized, "smart" auction process.

Practical advantages are derived from the competition and self-selection features of auctions. The term "smart" auction refers to an auction where a computer solves the complex combinatorial problem implicit in back-haul problems and reports the potential winning bidders. The feasibility of the idea is tested by application of new experimental techniques found in laboratory experimental economics.

The problem to be considered has two central features. First, the back-haul might be most efficiently achieved by some combination of several different transportation providers, each of which deals with only part of the entire stock that might be moved. Secondly, the costs of providers are unknown to the firm that wants to procure the back-haul services. The implication of the first is that the cost minimizing allocation will require some combination of appropriately coordinated service providers. The implication of the second is that the acquiring firm must use some form of competition in order to minimize costs. Previous smart market designs found in the literature[3] show promise in addressing these general issues in environments that differ significantly from the back-haul environment. The smart market outlined below is designed to solve these two problems in the back-haul environment.

Intuitively the process will operate through iterative periods of competition in which competing sellers will adjust their services and charges to "fit" into a least cost combination of transportation charges when meshed with the buyer's cost savings information. The buyer (rental company) posts a cost function giving the costs that they face if containers are not moved. These costs are a sum of storage costs at sink locations and opportunity costs for missed rentals at source locations. The sellers (transportation providers) are then involved in an iterative bidding process that resembles a 1st price procurement auction. Sellers post asking prices for moving units along particular routes. A computer will evaluate these offers in light of the cost function, and announce a set of potential winners and losers. The process will continue until no seller wishes to ask a

[3] McCabe, Rassenti, and Smith(1987) begins the exploration of a uniform price market design for gas/electric transportation networks that is continued in a series of later papers, but their market does not involve multiple routes between sources and destination that will be present in the back-haul problem. Our auction design will also allow all-or-nothing contracts, which may aid in situations where a competitive equilibrium does not exist at the price of introducing combinatorial optimization problems to the operation of the auction. See Rassenti, Smith and Bulfin (1982), Banks, et.al. (1989), Olson and Porter (1994), Brewer and Plott(1996), and Plott and Porter(1997), and Brewer(1998) for other examples of combinatorial auctions.

lower price for their transportation services. At that point, the potential allocation will become the actual allocation, and sellers will collect on their transportation contracts.

This paper reports on three fundamental questions. First, what is the formal representation of the process? Since this is not an auction of the usual sort, its dimensions must be made clear. Secondly, how will the process be defined in operational terms? Exactly what is known to participants and exactly how the auction works must be explained. Third, will it do what it is supposed to do? Since the tests of the auction uses laboratory experimental techniques some explanation is needed about how they are applied and what is learned from their application.

The remainder of the paper is organized as follows. Section II will present some major features of testbed and experimental methodology. Section III will provide needed background, notation, and concepts and discuss the class of transportation and backhaul problems under consideration. Section IV will define a formal testbed problem that will contain elements that any procurement auction must address. Section V will provide the rules of the smart procurement auction to be tested in this paper. Section VI presents theoretical cost and transportation benchmarks from competitive and monopsony theory. These benchmarks are not models of the auction, but rather are standards of performance to which we can compare the outcomes of the auction. Section VII presents experimental procedures. Section VIII presents the results. Section IX presents conclusions, and suggests avenues for future exploration.

II. LABORATORY TESTBED METHODOLOGY

The use of laboratory experimental techniques to "testbed" new types of processes is rapidly gaining in popularity. The idea is to create and implement prototypes of the process in laboratory environments. Individuals motivated by financial incentives compete under conditions that are controlled and understood from the point of view of the experimenter.

Such an exercise addresses several important issues. First, the fact that a prototype is constructed demonstrates that the ideas that support the process can be given a concrete and operational incarnation. That is, the abstract concepts have been replaced with real things and the concepts have an internal consistency. Secondly, the operations of the process can be studied and one can determine if the process performed as it was supposed to perform. It is a type of proof of principle. Does the process do what it is supposed to do? Thirdly, one can examine *design consistency* – asking whether the results were understandable in terms of the basic principles used in the design of the process or if the results were due to lucky chance. The role of "design consistency" in evaluating market prototypes is becoming well established (Plott, 1994). If a process is going to be scaled up to a business level it should be working for the right reasons, otherwise there is little reason to think that the results will survive the scaling. Finally, obtaining these answers is inexpensive when laboratory experimental methods are employed. Badly conceived, incompletely conceived or internally inconsistent processes will reveal themselves when it is not costly. Processes based on unreliable principles can be exposed through inexpensive tests. The idea of testbeds is simply to provide a "first pass" at developing new methods of doing business.

The basic "testbed" approach to testing allocation mechanism has precedence in the literature. This approach, initially described in Plott(1994) has been successfully applied in Brewer and Plott(1996) with regard to the BICAP auction for access to railroad tracks and in Plott and Porter(1996) with regard to auctions for access to NASA space station resources are accounts of the use of the procedure.

Testbeds involve three elements. The first is an environment that contains economic parameters of a model economic problem that is to be solved. This is outlined in section IV. The second element is the mechanism that is to be implemented – the prototype process. In this case it is a backhaul auction process to be developed and outlined in detail in Section V. Third is the set of criteria or performance measures by which performance of the mechanism is to be evaluated together with existing ideas about why the mechanism might perform as expected. The criteria are contained in Section VI.

In this case, four benchmarks are employed as standards for performance evaluation. The first is the lowest cost possibility, which is the case of vertical integration in which the purchasing firm has all of the cost functions of all providers and also has the power to administer what they do. The second benchmark is a monopsony in which the purchasing firm knows each provider's costs but must use similar payment terms with each provider. Two cases, single price and nonlinear pricing, are considered for the monopsony, who chooses prices strategically to obtain low costs. The third is the competitive model in which the derived demand from the firm's cost savings is in equilibrium with providers' marginal cost of transportation. The final benchmark involves sequential contracts, with the buyer meeting with each transportation provider in a sequence and, at each meeting, arranging a contract that maximizes total surplus in a myopic, non-forward looking, fashion. These benchmarks represent difficult challenges. Each assumes that either the buyer has information and/or powers that it does not have, or that competitive or strategic processes can operate in a way that is a bit unusual when there is only one buyer and only a few sellers.

III. BACKGROUND, NOTATION AND CONCEPTS

The purpose of this section is to roughly define a class of transportation environments in terms sufficient to explore the economic issues that are involved without overwhelming the reader with too much detail. Later sections will develop notation and detail needed for defining an experimental testbed and performing rigorous analysis.

Figure 1 shows a transportation problem that is trivial from size perspective but contains important challenges common across a wide class of transport management problems. Many environments involving the transport of homogeneous goods can be described by a figure similar in spirit to Figure 1.

In the figure, locations A and B have product waiting to be picked up, whereas locations D[4] and E are empty and are waiting for product to be delivered. The properties of a particular location are described with three parameters: a capacity K, the current stock S, and the target level T. Capacity K and stock S are physical properties. In contrast, the desired target level T depends on the economic property of a location as a pickup or delivery location and on local business conditions (which we take to be exogenous).

From the labels on Figure 1, one can see that the principal's target is to have the entire product at warehouses A (30 units) and B (30 additional units) picked up and delivered to the empty warehouses at locations D and E, which can each hold 30 units.

Agents

Two classes of agents operate in the environment of Figure 1: a single principal agent (denoted `P`) and several transportation provider agents (an individual agent denoted t_i).

In figure 1, a principal agent `P` owns the units of goods located at the warehouses at locations A, B, D, and E. The principal agent knows the capacities, current stock, and target levels at each warehouse, and knows what costs he faces if target levels of units are not met.

However, the principal agent can not move units. He must contract with transportation provider agents to move the units.

The transportation agents face costs for moving units. Costs vary from agent to agent and from route to route. Except where noted, each transportation agent's costs are private information known only to that agent.

Summary of Principal's Management Problem

The principal attempts to solve a cost minimization problem of the following form:

Choose a transportation strategy to
MINIMIZE
Principal's Total Cost = Cost of Moving Units + Cost of Unmoved Units
with respect to constraints:

(i) at each pickup location, units picked up can not exceed total stock of units
(ii) at each delivery location, units delivered can not exceed warehouse capacity K.
(iii) total units picked up must equal total units delivered

Put briefly, choosing a transportation strategy means that the principal will choose how many units to move at each location. This movement choice, along with the initial stock at each location, will give rise to a final level of stock at each location. The principal faces a tradeoff between costs for moving units and costs for not meeting targets. The constraints upon the principal is essentially that units can not be created or destroyed

[4] 'C' was not chosen to identify a location, to avoid confusion with later uses of 'C' to represent cost.

(total pickups can not exceed stock, and total pickups must equal total deliveries) and that the warehouse capacities can not be exceeded.

The complexity of this problem is suggested by the numerous variables on which the moving costs and the unmoved costs might depend. Clearly, the cost of moving units depends not only upon the number moved but also upon details of negotiation between the principal and the transportation providers.

Some initial insight into the problem can be obtained by separating the details of *routing* from the *resulting movements*. Distinguishing between these notions, as made clear in the next section, results in certain simplifications. This division of details is also used later in the design of the smart auction.

Principal's Choices: Movements vs. Routing

The principal must somehow choose how many units to move at each location. There are two levels of detail at which this choice can occur. The principal might specify a *movement vector* or a *routing vector*. The difference between these two specifications is illustrated below.

Definition. A *movement vector* $\mathbf{M} = (M_A, M_B, M_D, M_E)$ is a vector giving the net change in the number of units at each location.

Note that sign determines whether units being moved are pickups or deliveries. For example, if $\mathbf{M}$=(-20,-25,30,15), then 20 units are to be picked up at location A, 25 units are to be picked up at location B, 30 units are to be delivered to location D, and 15 units are to be delivered to location E.

Definition. A *routing vector* $\mathbf{r} = (r_{ad}, r_{ae}, r_{bd}, r_{be})$ gives the number of units to be moved along each route in the transportation network.

A routing vector is more specific than a movement vector. For any particular movement vector, there are many routing vectors that can achieve it. Figure 2 gives an example, showing how two different routing vectors $\mathbf{r}$ and $\mathbf{r}'$ can result in the same movement vector $\mathbf{M}$.

Properties of Testbed Environment

Four simple properties can be used to summarize this broad class of transportation environments. These mostly involve noticing what components of principal's or transportation provider's cost depend on moving vs. routing vectors. These properties act to summarize certain relationships that will become useful when choosing a bidding mechanism.

Property 1. In the testbed environment, a *target movement vector* can be defined as $\mathbf{M}_T = \mathbf{T} - \mathbf{S}$, where the vectors $\mathbf{T}$ and $\mathbf{S}$ give the target level and current stock at each location. However a *target routing vector* is not uniquely specified given the movement vector as many routing vectors result in the same movement vector.

Property 2. Principal's costs of unmoved units (not meeting targets) depend only upon the difference ($\mathbf{M}_T$-$\mathbf{M}$) between the target movement vector $\mathbf{M}_T$ and the chosen movement vector $\mathbf{M}$.

Property 3. A transportation provider's costs of moving units will depend upon the routing vector $\mathbf{r}_i$ chosen by that provider.

Property 4. The principal's costs of moving units depend upon the details of contracts between the principal and the transportation providers and the routing vector selected as a result of these contracts.

IV. THE EXPERIMENTAL TESTBED

The purpose of this section is to describe the testbed environments used in the experiments that follow.

The arrangement of pick up and drop off locations is the same as shown in Figure 1, i.e.

$\mathbf{X}$ = set of locations = {A,B,D,E},
$\mathbf{X}_{pick}$ = set of pick up locations = {A,B}, and
$\mathbf{X}_{drop}$ = set of drop off locations = {D,E}.

Agents have the same role as in the example, only now we will be specific about how many transportation agents there are and their cost functions for moving units. There is a principal agent P who wishes to obtain transportation from 12 transport agents t_1 .. t_{12} .
Thus, $\mathbf{I}$ = set of agents = { P , t_1 , t_2 , ..., t_{12} }

Principal's cost parameters.
The principal's cost function is

$$C_P = P^{moving}(\mathbf{M}) + C_P^{unmoved}(\mathbf{M}_T\text{-}\mathbf{M})$$

where $\mathbf{M}_T$ is the target movement vector and $\mathbf{M}$ is the movement vector chosen by the principal agent. The price $\mathbf{P}(\mathbf{M})$ paid to the transportation agents for moving the units will be determined in the experiments using a bidding mechanism to be described in the next section. The cost of unmoved units, $C_P^{unmoved}(\mathbf{M}_T\text{-}\mathbf{M})$, for this initial series of experiments, was chosen to have the quadratic form shown below:

$$C_P^{unmoved}(\mathbf{M}_T\text{-}\mathbf{M}) = 4\|(\mathbf{M}_T - \mathbf{M})\|^2 = 4\sum_{x \in X}(T_x - S_x - M_x)^2$$

Transportation agent cost parameters
The cost functions of each transportation provider are given in Table 1. Each row of the table shows the marginal cost functions of one particular agent. Costs of moving units over separate routes are additive. For example, if agent 5 moves 2 units along route ad and 3 units along route ae, then agent 5's cost is (45+180=225) along route ad and (144+216+300=660) along route ae, for a total cost of 225+660=885.

The cost functions of the various transportation agents were chosen as unrecognizable pieces of a linear total supply function. This relationship can be seen in Table 2. Let _[v]_ be the largest integer less than or equal to v (i.e. "rounding down"). Then the aggregate supply function for each route is as follows:

$S_{AD}(P_{AD}) = \_[P_{AD}/9]\_$
$S_{AE}(P_{AE}) = \_[P_{AE}/12]\_$
$S_{BD}(P_{BD}) = \_[P_{BD}/11]\_$
$S_{BE}(P_{BE}) = \_[P_{BE}/6]\_$

V. THE COMBINATORIAL BACHKAUL AUCTION MECHANISM

The Combinatorial Backhaul (CB) Auction is described by the following set of rules.

1. At each point in time, each transportation agent in the auction may have exactly one standing ask, of the form $A_i = (t_i, P_i, M_{iA}, M_{iB}, M_{iD}, M_{iE})$, where P_i is the price requested by agent t_i to remove M_{iA} units from location A, remove M_{iB} units from location B, deliver M_{iC} units to location C and deliver M_{iD} units to location D.
2. The auction starts with a null initial ask (t_i, 0, 0, 0 ,0 ,0) from each agent.
3. At each point in the auction, a computer calculates the set of asks that minimizes total costs to the principal agent P. This set of asks is called the *potential allocation*, and the cost to the principal agent is called the *potential principal cost*.
4. An agent t_i is allowed to replace his ask A_i with a new ask A_i* only if the effect on the potential principal cost is non-increasing.
5. If T_0 seconds elapse without an acceptable new ask from some agent, then the auction is concluded. The potential allocation becomes the final transportation contract. The principal must pay the transportation agents, and these agents must deliver the transportation services.

A central computer oversees the rules of the procurement auction. The auction operates as follows. Before the auction opens, the principal posts the cost function $C_P^{UNMOVED}$ and the target movement vector $\mathbf{M}_T$ to a public information area of the computer. When the auction opens, a timer is started at 60 seconds. Agents may submit asks consisting of a requested price for providing some movement vector of units. The computer determines whether this ask would be tentatively accepted or rejected, and, if not rejected, reports the new ask along with the potential allocation information to all agents. At any time, agents may revise their ask in a manner that is cost-decreasing to the principal, i.e. they may offer a lower price or offer to move more units for the same price. A soft termination rule is used, similar to the "going-going-gone" of oral auctions: the auction continues until the timer expires, but each new ask that is included into the potential allocation resets the timer for another 60 seconds. Therefore, the auction ends when no agent submits a cost-improving ask.

The following intuition plays a role in suggesting this particular auction organization. From Properties 1-4 of the preceding section, we see that the principal's cost function can be broken up into components according to whether movement or routing vectors are important. Details of routing are among the issues that determine transportation provider's costs but only movement is relevant to the principal. Thus, the auction is designed to let transportation providers determine the details of routing, with competition driving these providers to select lower cost routings over higher cost alternatives. Through asks, the transportation providers input the costs of movement for a computer to compare against the principal's cost of not moving units. The soft-closure action of the timer should assist in encouraging competition and terminating the auction when further cost-lowering is not possible.

VI. THEORETICAL BENCHMARKS AND STANDARDS OF PERFORMANCE

The purpose of this section is to provide some theoretical benchmarks against which to judge the behavior of the combinatorial backhaul auction observed in the experiments of the next section. These benchmarks are derived using standard assumptions of full-information and optimization on the part of agents and thus represent quite a challenge for a mechanism that will operate in an environment where agents have sparsely distributed information and perhaps do not fully optimize.

In order of increasing cost to the principal agent, the benchmarks include *vertical integration* (VI), *nonlinear pricing monopsony* (4P+Q), *single price monopsony* (1P), *competitive equilibrium* (CE), and *sequential contracting* (SC). A brief definition of each of these benchmarks is given below. The definitions are standard.

Calculations of benchmarks involved brute force optimization via computer, and therefore are not shown in detail. A sense of the process can be seen in the Figures 3-6 and Table 3. Figures 3-6 show the costs of procuring transportation along the various routes, using some of the benchmarks shown below. Table 3 shows similar calculations for a nonlinear monopsony pricing model. In each case, these figures represent intermediate results that give the cost of transporting units along a particular route. The benchmarks in Table 4 are then obtained by comparing the principal's total cost over every possible movement and routing vector.

Table 4 summarizes the outcome at each theoretical benchmark. The table can be read as follows: for vertical integration, the principal will face a total cost C_P of 3374 consisting of a cost of 2574 for moving units and cost of 800 for unmoved units. This least cost is achieved when 22 units are picked up from A, and of these, 13 delivered to D and 9 to E; and 24 units are picked up from B with 9 of these delivered to D and 15 to E. The totals delivered to a location are shown in parenthesis, e.g. under VI, a total of (22) units will be delivered to D and (24) delivered to E. Since the principal does not pay a constant price to the agents under vertical integration, we do not report a price per unit moved. However, in the 1P and CE benchmarks the relevant constant prices are reported.

<u>Vertical Integration (VI)</u>

Under vertical integration, the principal P controls each transportation agent t_i and therefore pays only the minimum cost of any desired transportation. Because the transportation agents operate at zero profit, the marginal procurement cost curve along a particular route is identical to the supply function for that route. The vertical integration cost benchmark is unique among the four we will use, because it involves the mathematically lowest cost. It is impossible to find a collection of contracts with lower total costs without forcing the transportation providers to operate at a loss.

Monopsony

Under monopsony, the principal P and transportation agents t_i are independent. The principal chooses parameters of a pricing contract, and the agents decide whether to move 0, 1, or more units under this contract. Two types of contracts are considered, one-price (1P) and nonlinear pricing (4P+Q).

- One-Price(1P) Monopsony

The principal chooses a price to pay per unit of transportation for each route, resulting in a 4-tuple of prices (P_{AD}, P_{AE}, P_{BD}, P_{BE}). This is called a "one-price" contract because there is no price discrimination over quantity moved or over individual agents. Different agents moving units on the same route receive the same price per unit moved.

- Nonlinear Pricing (4P+Q) Monopsony

The principal chooses a vector of prices to pay for various levels of transportation along each route. The name 4P+Q for this benchmark indicates that the principal may choose 4 prices for each route, plus a quota of contracts of each type to accept along that particular route should supply exceed the principal's needs. On each particular route a principal chooses a vector $\mathbf{P}$ = (P(1),P(2),P(3),P(4)) of prices to offer for moving 1, 2, 3, or 4 units along that particular route as well as a vector of quotas $\mathbf{Q}$ = (Q(1), Q(2), Q(3), Q(4)) of each contract type. In total, the principal chooses a total of 16 prices contained in the four vectors $\mathbf{P_{AD}}$, $\mathbf{P_{AE}}$, $\mathbf{P_{BD}}$, $\mathbf{P_{BE}}$ and 16 quotas contained in four vectors $\mathbf{Q_{AD}}$, $\mathbf{Q_{AE}}$, $\mathbf{Q_{BD}}$, $\mathbf{Q_{BE}}$. Notice that although the principal can engage in quantity-based price discrimination, he can not offer different prices to agents on any other criteria.

Competitive Equilibrium

A competitive equilibrium exists at the prices shown in Table 4. In competitive equilibrium, the principal pays a single price for all units moved along a particular route. The price along a particular route is such that the principal's demand for transportation, as derived from marginal cost savings, exactly equals the aggregate supply of transportation, as derived from marginal transportation costs. The equilibrium shown supports the least cost allocation of contracts. The movements of units are identical to those in least cost vertical integration. Because the principal does not capture the transporters' surplus, the total cost to the principal is much higher than in vertical integration.

Sequential Contracting (SC)

Under sequential contracting, the principal P negotiates with each transportation agent in sequence. That is, first P meets with t_1, then P meets with t_2, etc. At each meeting, the pair first considers route A to D, then route A to E, then route B to D, then route B to E. For purposes of creating a benchmark, assume that each meeting results in a contract that, *given information available at that moment*[5], reflects the greatest possible benefits from exchange. Prices for transportation services need only satisfy voluntary participation, implying a broad range of contract prices is possible: the principal could pay as little as the transportation provider's marginal cost or the principal could pay as much as his entire cost savings. While there is a range of possible total costs of moving the units under this benchmark, the number of units to be moved is rigidly defined.

Under sequential contracting, because the principal faces a high initial marginal cost of unmoved units and ignores future contract possibilities in his sequential maximization, he buys too much transportation in initial meetings. This results in much higher levels of movement than in any of the other benchmarks. Inefficiencies occur because the principal does not buy strictly from the lowest cost providers.

Allowing the principal to somehow renegotiate the initial contracts could tend to increase efficiency and lower costs. This is part of what we seek to accomplish automatically by designing a smart auction. Thus, the smart auction should hopefully provide consistently lower total costs than the sequential contracting benchmarks even if it can not attain low levels of cost associated with monopsony or vertical integration.

VII. EXPERIMENTAL PROCEDURES

The purpose of this section is to describe procedures used in conducting the experiments, whose results will be presented in the next section. A total of 7 experiments were conducted. The parameter choices along with basic properties of the data such as time periods and numbers of trades are summarized in Table 5.

Instructions

In each experiment, subjects were given the instructions found in the Appendix together with a cost information sheet (essentially, each agent sees a single row from Table 1) and forms to fill out to calculate their profits from any transportation contracts they might be awarded.

Data Issues: Paper vs. Computer

The form of the data generated in the experiment plays a role in determining convenient forms of initial analysis. In the experiments the subject's costs for transporting units along each route were provided on paper, along with extra sheets for recording revenues, costs, and profits from any transportation contracts awarded during the experiment. Each subject's paper work was checked for correctness at the end of each period. The computerized data consists of all asks entered into the auction along with the final outcome.

The choice to computerize only the auction institution and not the entire experiment involves a number of tradeoffs, both between programming labor and experimental data production as well as the level of generality of experiments that can be performed. This led to a design where the most convenient experimental data to analyze corresponds to

[5] Specifically, the principal does not consider what future contracts may be possible with the other agents, who have not yet been met.

the principal's point of view rather than to either the transportation agent's point of view or a global point of view.

Software Issues

The combinatorial backhaul auction was implemented as a web-page server system compatible with Netscape Navigator. The experimenter ran a web server on a computer that served as the control system, and each subject ran a copy of Netscape Navigator on standard windows-based PCs.

It can be difficult to use the web to design interactive markets, because ordinarily web technologies are based on *pull*. That is, they retrieve information only upon receiving specific requests from the user. This is a problem in a fast moving, continuous market, as it can be tiresome for the user to constantly request updates to the information on his screen, and almost impossible for the experimenter to know what information is on each user's screen. Therefore, there were significant technical challenges that had to be overcome in order to create a continuous market over the web.

Our software was specially designed to take advantage of special *client-pull/server-push* Netscape features which continuously updated information on the subjects screens, rather than relying upon subjects to request new information. Two versions of the software are worth distinguishing.

Experiments 1-3 were performed with version 1 of the software. In this version, watching the market information and submitting a new ask were separate activities that appeared on separate web pages. This issue is worth noting because while a subject was busy entering an order, they could not normally see the latest orders of others. Some subjects switched back and forth between the two web pages – which took time, while more computer literate subjects simply ran two copies of the Netscape program. Those who ran two copies of Netscape were able to see the latest orders in one window while they worked on entering their own order in another window.

Experiments 4-7 were performed with version 2 of the software. This version merged the various web pages by using the frames feature of Netscape. Subjects were able to both watch the activity and place new orders without having to switch web pages or otherwise manipulate the computer.

The result of this minor software change appears to be somewhat dramatic in terms of order flow and length of periods. Table 5 shows the number of asks to increase by a factor of 2 to 3 with the change in screen design from Experiments 1-3 to Experiments 4-7. It is interesting to note that the increased flow of asks does not cause the auction to end sooner.

VIII. EXPERIMENTAL RESULTS

Table 6 reports the raw data for the experiments. The table is broken up into two sections according to the demand target movement vector in the testbed. Recall that the different movement target vectors correspond to different cost functions for the principal on the demand side of the environment, and should lead to different allocations in the mechanism.

Each row of the table corresponds to the final outcome of a specific experimental period. The entries on each row are, from left to right, the costs to the principal for moving and not moving units, and the final allocation of transportation contracts that give rise to these costs. For example, in period 1 of experiment 1, the total cost to the principal was 7349, consisting of a cost of 5325 paid to the subjects (transportation providers) for moving units, and 2024 paid for the units that were unmoved. 39 units were moved, with 16 picked up at location A and 23 picked up at location B. Of these 39 units, 15 were delivered to D and 24 to E[6].

The pattern of results that follow compares the data reported in Table 6 to the theoretical benchmarks reported in Table 4. Comparisons will be made in three areas: principal's total cost, the relationship between moving costs and unmoved costs, and the flow of units. The goal is not to falsify any of the benchmarks as models but simply to use them as reference points in evaluating the total costs observed in the experiments. In addition, details of movement or routing in the benchmarks may help in further understanding the observed outcomes in the combinatorial backhaul auction experiments.

Result 1. Total costs of procurement in the combinatorial backhaul auction tend to be (a) below the sequential contracting benchmark, (b) within 10% of the competitive benchmark and (c) generally exceed the monopsony benchmarks and therefore exceed the minimum possible cost.
Support. Figure 7 provides a visual comparison of the principal's total costs observed in the experiments with the competitive equilibrium (CE), monoposny (1P, 4P+Q) and vertical integration (VI) benchmarks. (a) Only 3 of 31 (10%) periods are above the lower range of the sequential contracting (SC) benchmark in costs. These 3 occur under the 30-30-30-30 target (SC benchmark cost: 7500-14400) and are Experiment 1 Period 2 (total cost: 7860), Exp. 3 Per. 3 (total cost: 7883) and Exp. 4 Per. 1 (total cost: 8294). For all other cases the total cost is lower than the SC benchmark. (b) For the 30-30-30-30 target one can see that of the 21 total experiment-period observations, 3 observations are strictly within the CE band[7] of 5642-5985, and 15 observations are within 10% of the CE band (i.e., 5078-6583). For the 30-30-20-40 target one can see that of the 10 total observations, only one observation is strictly within the CE band of 6019-6239, and 7 are within 10% of the CE band (i.e., 5417-6862). If the data is pooled across both target levels, 22 of 31 periods (71%) of the periods have principal's final costs within 10% of the CE outcome, with the other 9 of 31 (29%) periods having costs greater than 10% above the CE range. (c) In the 30-30-30-30 environment, the 1P Monopsony benchmark is a total cost of 5218. Of the 21 observations for target 30-30-30-30, only 2 (Exp. 6 Per. 2, TC 5126 and Exp. 7 Per. 1, TC 5171) are below the 1P monopsony benchmark. In the 30-30-20-40 environment, the 1P Monopsony benchmark is a total cost of 5493. Of the 10

[6] It is worth reminding the reader that the routing of units is unobservable in the mechanism and is not reported. Thus, the table here lacks the routing detail present in Table 3.
[7] Recall that the CE benchmark involves a closed interval of values rather than a single number, because there is a range of market clearing prices rather than a unique price.

observations, only one, Exp. 4. Per. 5 (TC: 5436) is below the 1P monopsony benchmark. None of the experimental observations are below the 4P+Q Monopsony benchmark. •

Result 2. Comparisons of the cost of moving units (awarded procurement contracts) vs. the cost of unmoved units at the end of each experimental period tend to be more consistent with the competitive benchmark than with the other benchmarks.
Support. Figure 8 shows the relevant comparisons. Note that the 1P and 4P+Q monopsony benchmarks tend to decrease total costs by bearing a higher cost for unmoved units while manipulating the contract prices to achieve lowered moving costs. In general, the total cost of the moving contracts tends to be near the CE benchmark with a higher cost for unmoved units moved than would be expected at the CE. With one exception (Exp. 4 Per. 1), the cost tradeoff data is not at all consistent with any of the monopsony or vertical integration benchmarks. The SC benchmark is off the scale to the right in each case, and none of the experimental outcomes approaches this benchmark•

Result 3. Flows of units in the combinatorial backhaul auction are closer to the competitive/VI benchmark (30-30-30-30 case) than to any monopsony benchmark.
Support. Table 7 compares the observed flows from transportation contracts with the theoretical benchmarks. Table 7A examines the data for experimental periods involving the 30-30-30-30 target, whereas Table 7B examines the experimental periods involving the 30-30-20-40 target. In each table, the experimental observation of the movement vector and the theoretical benchmark movement vector are compared using the Euclidean norm:

$$dist = \sqrt{\sum_{x\in\{A,B,D,E\}} (M_x^{OBSERVED} - M_x^{THEORY})^2} .$$

The results show that at each target level, the CE/VI benchmarks[8] agreed best with the experimental observations regarding the flow of units in two ways: (1) averaged over all periods, the distance between the actual observations and the CE/VI benchmarks is lower than with the monopsony benchmarks, (2) counting periods, the CE/VI benchmark is closer than the others in predicting the outcome in 13 of 21 of the 30-30-30-30 target periods and 7 of 10 of the 30-30-20-40 target periods for a total of 20/31 (64%) of the periods•

IX. CONCLUSIONS

This paper constructs a computerized procurement auction capable of handling back haul and similar transportation problems involving the transportation of homogeneous goods under conditions of limited information about seller costs and a limited number of competing sellers. A testbed was developed to provide an initial challenge that any process for making back haul decisions must solve. An auction was designed and tested through laboratory experiments with cash motivated subjects. The outcomes compared to a set of theoretical benchmarks from both competitive and monopsony theory with a perfectly informed buyer.

[8] Recall that the CE benchmark and the VI benchmark both predict that the movement of units will correspond to an efficient movement of units. Thus the flows of units in these benchmarks are identical even though the costs to the principal vary.

The initial results are clear. Such an auction can be constructed and successfully implemented. Results 1-3 above summarize our findings relative to the performance benchmarks. The auction system produced costs much lower than the cost to the agent if the agent performed the functions "in house". Even though the in house cost to the agent were public information to the bidders, the auction resulted in lower cost.

The cost of back haul that resulted from the auction were lower than the negotiated price benchmark. The back haul cost to the agent were roughly comparable to what would have been the case if the back haul services were provided in a series of competitive markets in which prices were equal to marginal cost of the service. This is rather remarkable since no such markets existed.

The auction system did not perform as well as would have been the case of a perfectly informed monopsonist, who strategically used buying power to influence prices. Of course the combination of such information and buying power is very special set of circumstances and if available, there is little need for the firm to consider any form of procurement other than price setting. Nevertheless, the all-knowing monopsonist measure is an objective yardstick against which the performance of a less informed and powerful method of purchase can be measured. Clearly, if the buyer has some knowledge of seller costs and the opportunity, a strategic revelation of cost might be a useful tool to get back haul costs down even lower; but. such issues are well beyond the scope of this paper.

The auction would not perform as well as an integrated firm that owns all suppliers, is fully informed about all costs and provides itself with the services at the lowest possible cost based on the perfect information. In a sense such a buyer is even more powerful than the perfectly informed monopsonist unless the monopsonist is able to implement perfect price discrimination. This measure reflects the best any procurement system could do, so it is a natural yardstick to apply.

Results 2 and 3 tell us that the way to understand this form of back haul auction is by application of the competitive model. Under competitive conditions the purchasing firm is supplied all aspects at prices equal to the marginal cost of the suppliers. It is quite remarkable that the auction performance is similar to that predicted by the competitive model given the substantial latitude for strategic behavior, poor coordination missed opportunities, etc. From the point of view of potential users, the results suggest that the competitive model is the appropriate benchmark. If analysis suggests that organized competition would produce lower cost than its current procurement method then the purchasing firm should consider this form of auction as a replacement.

Future analysis should take into consideration the dynamics of the process. The current analysis is primarily concerned with the outcomes at the end of each period rather than with the process by which the outcomes are achieved. Details of the dynamics may yield insights into how to alter the process. For example, an analysis of the bidding process might show a tendency towards certain kinds of one stage Nash equilibrium as reported for the BICAP auction in Brewer and Plott(1996), or it might operate in a different manner. Analysis could also be extended to explore major aspects of procurement not studied here, such as quality of service, reliability, timing, etc.

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APPENDIX A: ORIGINAL WEB-BASED INSTRUCTIONS FOR EXPERIMENTS.

GENERAL INSTRUCTIONS

This is an experiment in the economics of market decision making. The instructions are simple and if you follow them carefully you might earn a considerable amount of money that will be paid to you in cash.

You will be trading in an electronic market of a number of market trading periods or days. You will be selling items which are supplied to you at a cost. Attached you will find a set of cost sheets, one for each period, which describes the value to you of any decisions you might make. You are not to reveal this information to anyone. It is your own private information.

The currency in this market is called francs. All profits and losses will be in terms of francs. At the end of the experiment francs will be converted to dollars at the rate of

___ 100 ____ francs = 1 US dollar or 1 franc = ___ cents. You will be paid in dollars.

SPECIFIC INSTRUCTIONS

You will be bidding in a market to provide transportation services to move items among locations. We will call the items "units" and the locations will be called A, B, C, and D. This market will be carried out using the computer terminals.

Each period there will be a public announcement about how many units that need to be moved. This includes the number to be moved from some locations and the number to be delivered at other locations. In the market you will have an opportunity to bid on moving some or all of the units that might be moved. You will be able to ask any price that you like for moving units, but the computer will have the freedom to reject your bid in favor of another bid. Only if your bid is accepted will you get a final contract and you will be paid only on final contracts that you obtain. How this works will be explained later.

Your profit in a period consists of the price you receive on any final contracts minus the cost to you of moving the units specified in those contracts. The costs to you of moving units are given on a set of attached cost sheets. You only pay these costs if you get a final contract to move the units.

PERIOD PROFIT = CONTRACT REVENUE (your bid) - TRANSPORTATION COST

Example: Suppose you get a final contract to move 4 units from A to B and move 3 units from C to D. Suppose your bid for all this transportation was 1300. If your cost is 500 for moving 4 units from A to B and 450 for moving 3 units from C to D, then your total transportation cost is 500 + 450 = 950. Your profit is the contract revenue of 1300 minus the transportation cost of 950:

$$\text{profit} = 1300-950=350.$$

In some periods you might have a profit and other periods you might have a loss. Losses are deducted from any profits or other earnings you might have. Your total earnings will be the sum of any profits minus the sum of any losses.

DETERMINATION OF CONTRACTS

In determining the contracts to be awarded the computer performs a cost minimization calculation. The computer is able to move units itself at a cost and it will do so as long as its costs are less than the cost of contracts. In other words the computer only agrees to contracts to the extent that it saves itself money.

The cost to the computer go up when it is required to move things among the various locations itself. The formula for calculating the cost to the computer is four times the square of what it moves from a location or to a location. That is, if m_i is the amount the computer moved from/to, (negative m_i)/(positive m_i), location i then the total cost computer of computer moves is $_i$ 4 $m_i^{\,2}$. { If n_i is the amount that needs to be moved and x_i is the amount moved by contract with subjects then $m_i = n_i - x_i$ } The total cost of moves would be the cost of computer moves plus the cost of contract moves. The table will help you develop some intuition about the cost of moves by the computer. This could be useful because you know that unless your bid will save the computer money, the computer will do it itself.

Contracts are selected by the computer to minimize the total cost of movements. That is the computer looks among all bids and selects the set of contracts which might be made final. Total cost of a set of contracts is the cost of the contracts plus the cost to the computer of those movements not covered by the contracts (computed by the above formula). It will always find the lowest total cost set of contracts. If you submit a bid that lowers total cost from the computer's point of view, it will be selected.

When the market opens you are free to submit a bid. The bid will be a proposed movement of units from some locations and a deposit of units at some other locations. Your bid will also include the amount that you will charge for the movements.

The computer will announce a set of "tentatively selected" bids. The process will continue in this manner until no new bids are submitted. If no new bids are submitted within a specified period of time the tentatively selected bids will become the final selection.

The computer can only accept one bid from you at a time. This should cause no complications. You will be free to cancel any bid you make as long as it is not tentatively accepted, and then submit another. When bids are tentatively accepted they cannot be canceled so be sure that you have not made a mistake and are willing to deliver on a bid before you send it in. Since the computer will always accept "better" bids, you can always "improve" your bid by submitting the old bid, the tentatively selected one, augmented by however you might want. The old bid will be "deselected" and replaced by your new bid.

HOW TO USE THE COMPUTER

Logging On - You should already be logged on. This is in case you get lost.

I. Open Netscape.

II. Go to the URL: http://eeps2.caltech.edu/~transexp

Getting the Current List of Contracts

From the login page, click on:

"Examine the Current Potential Allocation"

This data changes rapidly as new bids are entered in the market.

How to Read the List of Contracts

The computer constantly calculates what it will do if no further offers come in. BLUE contracts would be accepted if no further bids were sent in.

RED contracts would NOT be accepted if no further bids were sent in.

Other Items on the contract page

Buyer DEMAND: Number of units that must be moved at each location.

Bidder Total: Total units that would be moved by BLUE contracts.

Buyer Makeup: The units that would have to be moved by the computer.

Makeup Costs: The cost of the computer moving the units itself.

(Makeup Cost = $4*\text{makeup}^2$)

Total Costs to BUYER: The cost of the BLUE contracts + Makeup Costs

Remember, the computer is the BUYER, and it always looks for minimum costs.

Sending in a Offer to Move Units

Go to the Bid Submission Form (an example is attached)

If not on the bid form, click on Bidding Forms at bottom of page to get it.

You must enter all the required data for your offer to be processed.

Enter your id number and password at the top of the bid form.

(You must do this each time you bid)

I. Enter the price you wish to charge for moving these units.

II. Enter the number of units you will pick up and drop off at each location.

III. Check for accuracy. It is difficult for us to correct typos.

IV. Click on SEND to send it. Nothing happens until SEND is hit.

Making a New Offer

If you make a MISTAKE or TYPO, you must bring it to our attention as soon as possible so that we can erase it. Otherwise, you may be required to honor the offer.

If your contract is in BLUE, that is if it is potentially accepted, then you can only change the contract in ways that lowers the computer's total moving cost. For example, you could reduce the price.

If your contract is in RED, that is if it is not potentially accepted, then you can make any change that you like, such as: raising or lowering the price, change the number of units moved, or withdrawing the offer.

Bid Submission Form

Top of Form

ID Number: Password:

Cash Asking Price: _

Pick Up Units: ***A:*** ***B:***

Deliver Units: ***D:*** ***E:***

*

SEND	CLEAR

This form can be used to:

- **submit a new bid**
- **revise an existing bid**
  Revision of bids that are in the blue/acceptable state is limited to those that lower the price or provide better service, as decided by the computer.
- **remove a bid in the** Red/unacceptable **state**
  To remove a bid, fill in ID and PASSWORD and hit SEND, leaving the other fields blank.

Abort and return to Home Page.

Be sure to double-check your entries before hitting SEND.

Bottom of Form

Table 1. Marginal costs of movement in the testbed of twelve agents.

t_i	Marginal Cost Route A to D ---------unit---------				Marginal Cost Route A to E ---------unit---------				Marginal Cost Route B to D ---------unit---------				Marginal Cost Route B to E ---------unit---------			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
1	9	216	225	432	192	264	276	372	132	264	396	407	72	96	216	240
2	18	207	279	423	180	252	348	384	121	253	330	418	66	90	210	234
3	27	198	234	414	168	240	288	396	110	242	385	429	60	84	204	228
4	36	189	288	405	156	228	360	408	99	231	319	440	54	78	198	222
5	45	180	243	396	144	216	300	420	88	220	374	451	6	30	150	174
6	54	171	297	387	12	132	204	432	77	209	308	462	12	36	156	180
7	63	162	252	378	120	312	444	576	66	198	363	473	18	42	162	186
8	72	153	306	369	24	108	456	564	55	187	297	484	24	48	168	192
9	81	144	261	360	96	324	468	552	44	176	352	495	102	126	246	270
10	90	135	315	351	36	84	480	540	33	165	286	506	108	132	252	276
11	99	126	270	342	72	336	492	528	22	154	341	517	114	138	258	282
12	108	117	324	333	48	60	504	516	11	143	275	528	120	144	264	288

Table 2. Supply functions for movement along each route.

SUPPLY FROM A TO D			SUPPLY FROM A TO E			SUPPLY FROM B to D			SUPPLY FROM B to E		
Unit #	MC	Assigned To	Unit#	MC	Assigned To	Unit #	MC	Assigned To	Unit#	MC	Assigned To
1	9	1	1	12	6	1	11	12	1	6	5
2	18	2	2	24	8	2	22	11	2	12	6
3	27	3	3	36	10	3	33	10	3	18	7
4	36	4	4	48	12	4	44	9	4	24	8
5	45	5	5	60	12	5	55	8	5	30	5
6	54	6	6	72	11	6	66	7	6	36	6
7	63	7	7	84	10	7	77	6	7	42	7
8	72	8	8	96	9	8	88	5	8	48	8
9	81	9	9	108	8	9	99	4	9	54	4
10	90	10	10	120	7	10	110	3	10	60	3
11	99	11	11	132	6	11	121	2	11	66	2
12	108	12	12	144	5	12	132	1	12	72	1
13	117	12	13	156	4	13	143	12	13	78	4
14	126	11	14	168	3	14	154	11	14	84	3
15	135	10	15	180	2	15	165	10	15	90	2
16	144	9	16	192	1	16	176	9	16	96	1
17	153	8	17	204	6	17	187	8	17	102	9
18	162	7	18	216	5	18	198	7	18	108	10
19	171	6	19	228	4	19	209	6	19	114	11
20	180	5	20	240	3	20	220	5	20	120	12
21	189	4	21	252	2	21	231	4	21	126	9
22	198	3	22	264	1	22	242	3	22	132	10
23	207	2	23	276	1	23	253	2	23	138	11
24	216	1	24	288	3	24	264	1	24	144	12
25	225	1	25	300	5	25	275	12	25	150	5
26	234	3	26	312	7	26	286	10	26	156	6
27	243	5	27	324	9	27	297	8	27	162	7
28	252	7	28	336	11	28	308	6	28	168	8
29	261	9	29	348	2	29	319	4	29	174	5
30	270	11	30	360	4	30	330	2	30	180	6
31	279	2	31	372	1	31	341	11	31	186	7
32	288	4	32	384	2	32	352	9	32	192	8
33	297	6	33	396	3	33	363	7	33	198	4
34	306	8	34	408	4	34	374	5	34	204	3
35	315	10	35	420	5	35	385	3	35	210	2
36	324	12	36	432	6	36	396	1	36	216	1
37	333	12	37	444	7	37	407	1	37	222	4
38	342	11	38	456	8	38	418	2	38	228	3
39	351	10	39	468	9	39	429	3	39	234	2
40	360	9	40	480	10	40	440	4	40	240	1
41	369	8	41	492	11	41	451	5	41	246	9
42	378	7	42	504	12	42	462	6	42	252	10
43	387	6	43	516	12	43	473	7	43	258	11
44	396	5	44	528	11	44	484	8	44	264	12
45	405	4	45	540	10	45	495	9	45	270	9
46	414	3	46	552	9	46	506	10	46	276	10
47	423	2	47	564	8	47	517	11	47	282	11
48	432	1	48	576	7	48	528	12	48	288	12

Table 3. (4P+Q) Monopsony benchmark outcomes along route ad.

Q	Total Cost	P 1 unit	P 2units	P 3units	P 4units	S 1 unit	S 2units	S 3units	S 4units	Quota 1units	Quota 2units	Quota 3units	Quota 4units
1	10	10	0	0	0	1	0	0	0	1	0	0	0
2	38	19	0	0	0	2	0	0	0	2	0	0	0
3	84	28	0	0	0	3	0	0	0	3	0	0	0
4	148	37	0	0	0	4	0	0	0	4	0	0	0
5	230	46	0	0	0	5	0	0	0	5	0	0	0
6	330	55	0	0	0	6	0	0	0	6	0	0	0
7	448	64	0	0	0	7	0	0	0	7	0	0	0
8	556	55	226	0	0	6	6	0	0	6	1	0	0
9	674	64	226	0	0	7	5	0	0	7	1	0	0
10	782	55	226	0	0	6	6	0	0	6	2	0	0
11	900	64	226	0	0	7	5	0	0	7	2	0	0
12	1008	55	226	0	0	6	6	0	0	6	3	0	0
13	1126	64	226	0	0	7	5	0	0	7	3	0	0
14	1234	55	226	0	0	6	6	0	0	6	4	0	0
15	1352	64	226	0	0	7	5	0	0	7	4	0	0
16	1460	55	226	0	0	6	6	0	0	6	5	0	0
17	1578	64	226	0	0	7	5	0	0	7	5	0	0
18	1686	55	226	0	0	6	6	0	0	6	6	0	0
19	1812	46	226	0	0	5	7	0	0	5	7	0	0
20	1956	37	226	0	0	4	8	0	0	4	8	0	0
21	2118	28	226	0	0	3	9	0	0	3	9	0	0
22	2298	19	226	0	0	2	10	0	0	2	10	0	0
23	2496	10	226	0	0	1	11	0	0	1	11	0	0
24	2712	0	226	0	0	0	12	0	0	0	12	0	0
25	2938	0	226	452	0	0	11	1	0	0	11	1	0
26	3182	0	226	461	0	0	10	2	0	0	10	2	0
27	3444	0	226	470	0	0	9	3	0	0	9	3	0
28	3724	0	226	479	0	0	8	4	0	0	8	4	0
29	4022	0	226	488	0	0	7	5	0	0	7	5	0
30	4337	0	226	479	839	0	7	4	1	0	7	4	1
31	4635	0	226	488	839	0	6	5	1	0	6	5	1
32	4968	0	226	479	848	0	6	4	2	0	6	4	2
33	5337	0	226	470	857	0	6	3	3	0	6	3	3
34	5737	0	226	524	867	0	3	8	1	0	3	8	1
35	6086	0	226	506	884	0	4	5	3	0	4	5	3
36	6412	0	226	524	884	0	2	8	2	0	2	8	2
37	6775	0	226	524	885	0	2	7	3	0	2	7	3
38	7114	0	226	515	893	0	2	6	4	0	2	6	4
39	7464	0	0	532	892	0	0	9	3	0	0	9	3
40	7828	0	0	532	893	0	0	8	4	0	0	8	4
41	8166	0	0	523	901	0	0	7	5	0	0	7	5
42	8550	0	0	523	902	0	0	6	6	0	0	6	6
43	8940	0	0	514	910	0	0	5	7	0	0	5	7
44	9344	0	0	514	911	0	0	4	8	0	0	4	8
45	9786	0	0	505	919	0	0	3	9	0	0	3	9
46	10210	0	0	505	920	0	0	2	10	0	0	2	10

Table 4. Theoretical benchmarks for the testbed environment.

Target $\mathbf{M}_T$: 30-30-30-30

	Principal's Total Cost = Cost of Moving Units + Cost of Unmoved Units			Pickups	Deliveries		Price per unit moved (where applicable)			
Benchmark	Total Cost	C_{moving}	$C_{unmoved}$		D	E	P_{ad}	P_{ae}	P_{bd}	P_{be}
VI Vertical Integration	3374	2574	800	A (22) B (24)	13 9 (22)	9 15 (24)	---	---	---	---
1P Monopsony One Price	5218	3434	1784	A (18) B (21)	11 8 (19)	7 13 (20)	100	85	89	79
4P+Q Monopsony Nonlinear P	4528	3624	904	A (23) B (22)	17 6 (23)	6 16 (22)	---	---	---	---
CE Competitive Equilibrium	5642 to 5985	4842 to 5185	800	A (22) B (24)	13 9 (22)	9 15 (24)	120 to 127	109 to 120	104 to 111	91 to 97
SC Sequential Contracting	7500 to 14400	7396 to 14296	104	A (26) B (30)	15 12 (27)	11 18 (29)	---	---	---	---

Target $\mathbf{M}_T$: 30-30-20-40

	Principal's Total Cost = Cost of Moving Units + Cost of Unmoved Units			Pickups	Deliveries		Price per unit moved (where applicable)			
Benchmark	Total Cost	C_{moving}	$C_{unmoved}$		D	E	P_{ad}	P_{ae}	P_{bd}	P_{be}
VI Vertical Integration	3546	2658	888	A(21) B(25)	10 6 (16)	11 19 (30)	---	---	---	---
1P Monopsony One Price	5493	3397	2096	A(17) B(21)	8 5 (13)	9 16 (25)	73	109	56	97
4P+Q Monopsony Nonlinear P	4932	3612	1320	A(21) B(22)	12 4 (16)	9 18 (27)	---	---	---	---
CE Competitive Equilibrium	6019 to 6239	5131 to 5351	888	A(21) B(25)	10 6 (16)	11 19 (30)	96 to 100	144	67 to 78	115 to 121
SC Sequential Contracting	7391 to 15200	7311 to 15120	80	A (27) B (29)	11 8 (19)	16 21 (37)	---	---	---	---

Table 5. Experiment parameters and level of observed activity.

Experiment	Date Time	Periods	Period 1 M_T=(30,30,30,30)		Period 2 M_T=(30,30,30,30)		Period 3 M_T=(30,30,30,30)		Period 4 M_T=(30,30,20,40)		Period 5 M_T=(30,30,20,40)	
			Time (sec)	Asks	Time (sec)	Asks	Time (sec)	Asks	Time (sec)	Asks	Time (sec)	Asks
1	960921 12noon	5	597	96	464	94	473	97	479	97	475	104
2	960921 5pm	5	680	116	599	143	583	129	602	131	594	137
3	960921 8pm	3	1913	301	362	88	329	44	---	---	---	---
4	961130 5pm	5	938	127	818	116	1031	134	670	113	1759	285
5	961201 4pm	5	1447	164	841	104	832	90	1836	249	1793	205
6	970111 1pm	4	1300	231	1509	252	2553	456	2228	405	---	---
7	970111 8pm	4	2865	580	2309	386	2109	386	1942	404	---	---

Table 6. Observed final allocations for each experimental period.

Target (30,30,30,30)						Pickups		Deliveries	
Experiment	Period	Total Cost	Moving Cost	Unmoved Cost	Units Moved	M_A	M_B	M_C	M_D
1	1	7349	5325	2024	39	16	23	15	24
	2	7860	6100	1760	40	16	24	18	22
	3	7277	5781	1496	41	20	21	18	23
2	1	6392	4928	1464	41	19	22	21	20
	2	6297	5169	1128	44	19	25	20	24
	3	6427	4883	1544	41	17	24	20	21
3	1	5708	4884	824	47	20	27	21	26
	2	7093	5453	1640	40	19	21	18	22
	3	7883	6051	1832	39	17	22	18	21
4	1	8294	5430	2864	34	13	21	15	19
	2	6005	4797	1208	43	21	22	19	24
	3	6088	5240	848	46	21	25	21	25
5	1	5501	4885	616	48	22	26	23	25
	2	6107	5203	904	45	22	23	22	23
	3	6016	4912	1104	44	19	25	21	23
6	1	5942	4974	968	45	20	25	21	24
	2	5126	4510	616	48	22	26	23	25
	3	5976	5112	864	46	20	26	22	24
7	1	5171	4235	936	45	21	24	21	24
	2	6186	5218	968	45	21	24	20	25
	3	6114	5162	952	45	20	25	23	22

Target (30,30,20,40)						Pickups		Deliveries	
Experiment	Period	Total Cost	Moving Cost	Unmoved Cost	Units Moved	M_A	M_B	M_C	M_D
1	4	7262	5174	2088	39	15	24	14	25
	5	7046	5750	1296	44	19	25	17	27
3	4	6812	5588	1224	44	18	26	15	29
	5	6721	5625	1096	47	19	26	16	29
4	4	7220	5804	1416	43	18	25	16	27
	5	5436	4396	1040	46	19	27	17	29
5	4	6224	5448	776	48	21	27	18	30
	5	5831	5055	776	48	21	27	18	30
6	4	6049	5313	736	48	22	26	18	30
7	4	5651	4875	776	48	21	27	18	30

Table 7A. Comparison of theoretical movement benchmarks with experimental observations. M_T=(30,30,30,30)

		Observed Pickups		Deliveries		Distance from Theoretical Benchmarks (Euclidean norm)		
Experiment	Period	M_A	M_B	M_C	M_D	CE/VI M_A,M_B,M_C,M_D 22,24,22,24	1P M_A,M_B,M_C,M_D 18,21,19,20	4P+Q M_A,M_B,M_C,M_D 23,22,23,22
1	1	16	23	15	24	9.27	6.32	10.86
	2	16	24	18	22	7.48	4.24	8.83
	3	20	21	18	23	5.48	3.74	6.00
2	1	19	22	21	20	5.48	2.45	4.90
	2	19	25	20	24	3.74	5.83	6.16
	3	17	24	20	21	6.16	3.46	7.07
3	1	20	27	21	26	4.24	8.94	7.35
	2	19	21	18	22	6.16	2.45	6.48
	3	17	22	18	21	7.35	2.00	7.87
4	1	13	21	15	19	12.81	6.48	13.19
	2	21	22	19	24	3.74	5.10	4.90
	3	21	25	21	25	2.00	7.35	5.10
5	1	22	26	23	25	2.45	9.06	5.10
	2	22	23	22	23	1.41	6.16	2.00
	3	19	25	21	23	3.46	5.48	5.48
6	1	20	25	21	24	2.45	6.32	5.10
	2	22	26	23	25	2.45	9.06	5.10
	3	20	26	22	24	2.83	7.35	5.48
7	1	21	24	21	24	1.41	6.16	4.00
	2	21	24	20	25	2.45	6.63	5.10
	3	20	25	23	22	3.16	6.32	4.24
Average Distance from Benchmarks						4.57	5.76	6.21

Table 7B. Comparison of theoretical movement benchmarks with experimental observations. M_T =(30,30,20,40)

		Observed Pickups Deliveries				Distance from Theoretical Benchmarks (Euclidean norm)		
Experiment	Period	M_A	M_B	M_C	M_D	CE/VI M_A,M_B,M_C,M_D 21,25,16,30	1P M_A,M_B,M_C,M_D 17,21,13,25	4P+Q M_A,M_B,M_C,M_D 21,22,16,27
1	4	15	24	14	25	8.12	3.74	6.93
	5	19	25	17	27	3.74	6.32	3.74
2	4	18	26	15	29	3.46	6.78	5.48
	5	19	26	16	29	2.45	7.35	4.90
4	4	18	25	16	27	4.24	5.48	4.24
	5	19	27	17	29	3.16	8.49	5.83
5	4	21	27	18	30	2.83	10.10	6.16
	5	21	27	18	30	2.83	10.10	6.16
6	4	22	26	18	30	2.45	10.00	5.48
7	4	21	27	18	30	2.83	10.10	6.16
Average Distance from Benchmarks						3.61	7.85	5.51

Figure 1. Model Transportation Environment

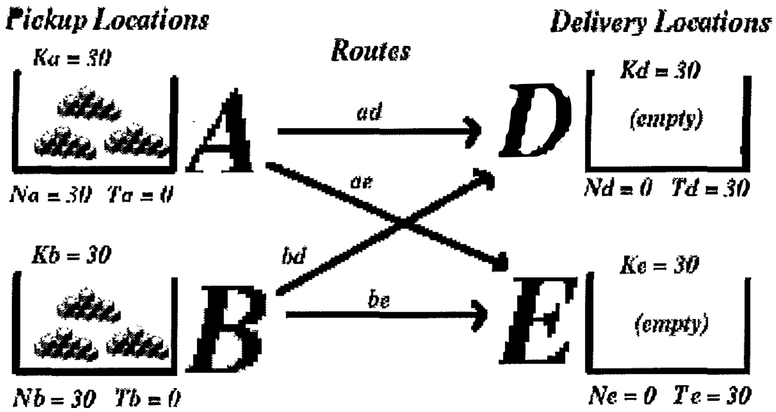
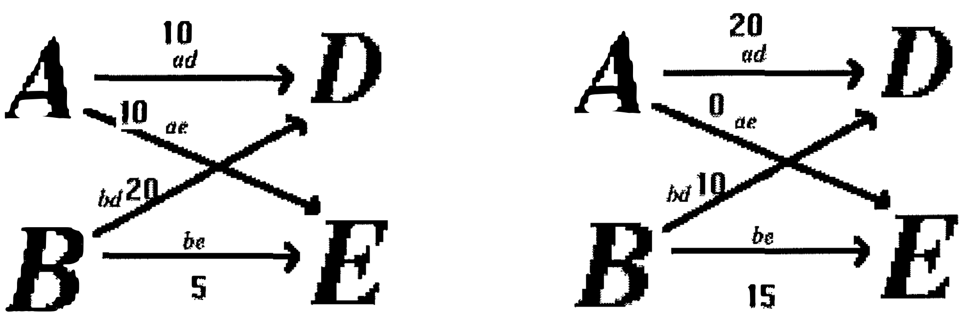
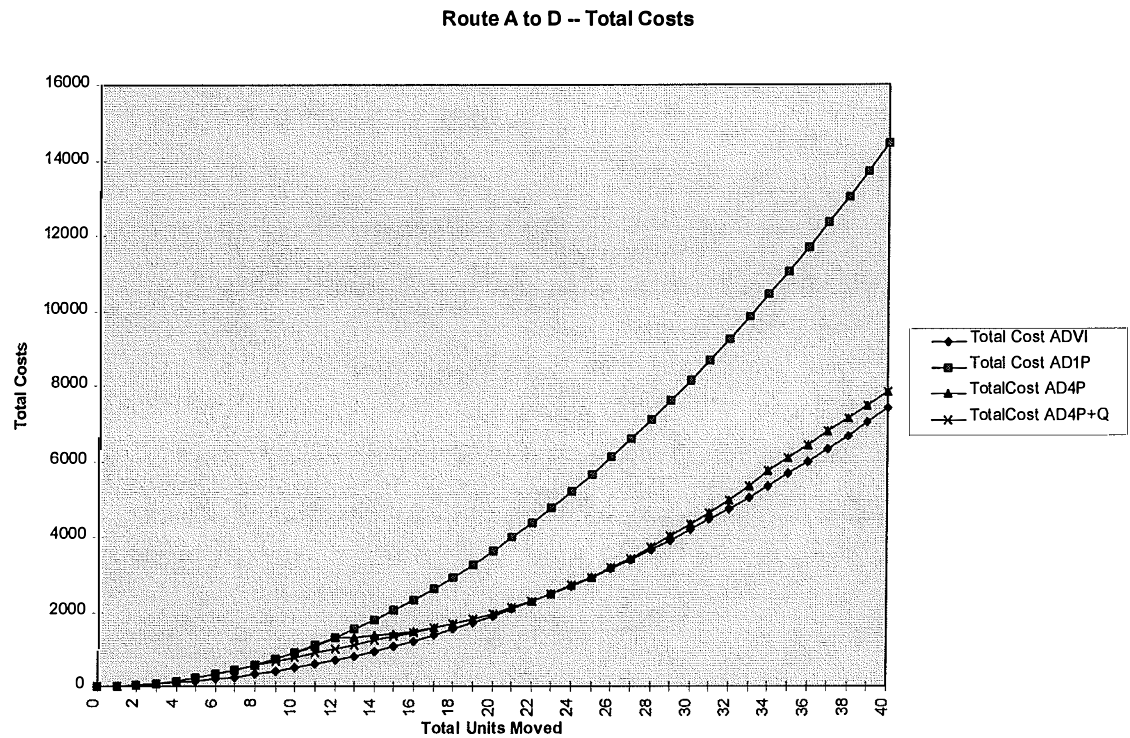


Figure 2. Different routing vectors can lead to the same movement vector.



	r_{ad}	r_{ae}	r_{bd}	r_{be}	$M_A = -(r_{ad}+r_{ae})$	$M_B = -(r_{bd}+r_{be})$	$M_D = (r_{ad}+r_{bd})$	$M_E = (r_{ae}+r_{be})$
r	10	10	20	5	-20	-25	30	15
r′	20	0	10	15	-20	-25	30	15

Figure 3.


Route A to D -- Total Costs
16000
14000
12000
10000
8000
6000
4000
2000
0
Total Costs
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
Total Units Moved
Total Cost ADVI
Total Cost AD1P
TotalCost AD4P
TotalCost AD4P+Q

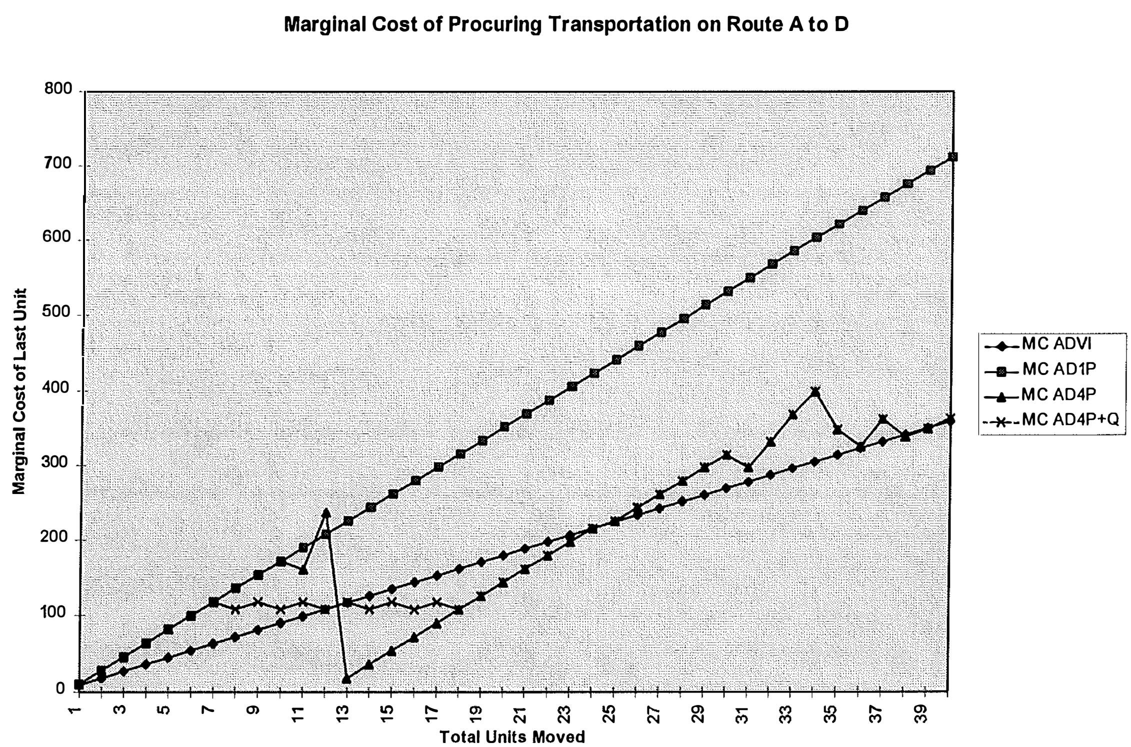

Marginal Cost of Procuring Transportation on Route A to D
800
700
600
500
400
300
200
100
0
Marginal Cost of Last Unit
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
Total Units Moved
MC ADVI
MC AD1P
MC AD4P
MC AD4P+Q

Figure 4.

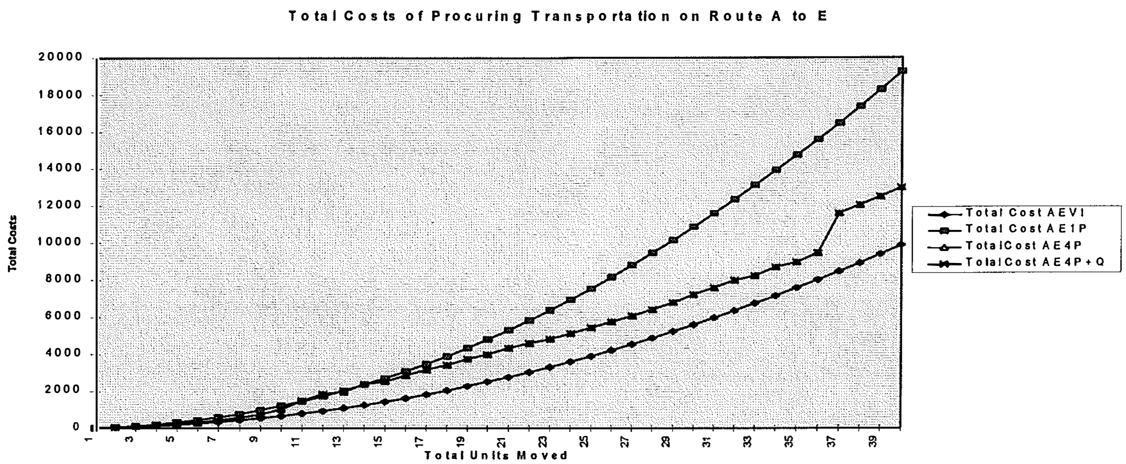


Figure 5.

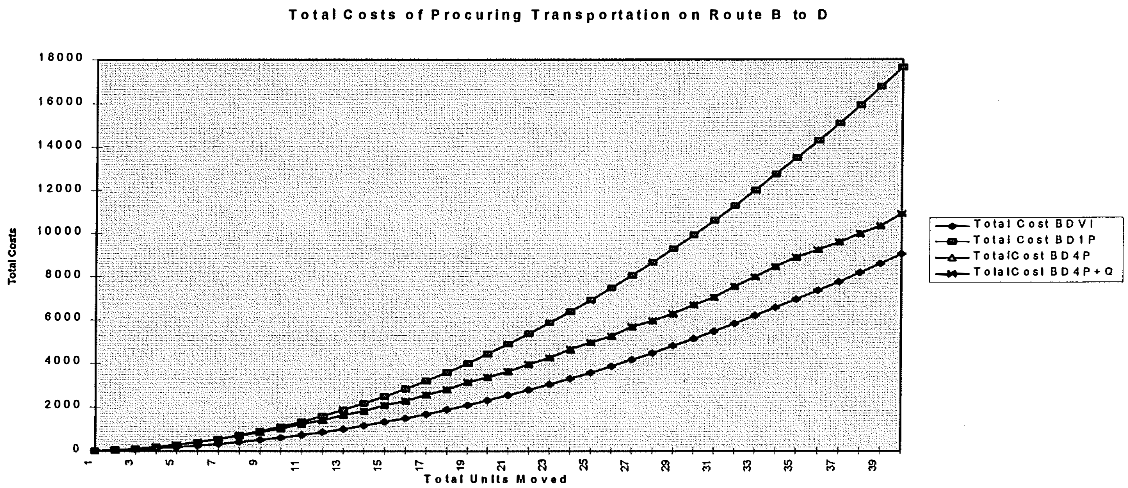


Figure 6

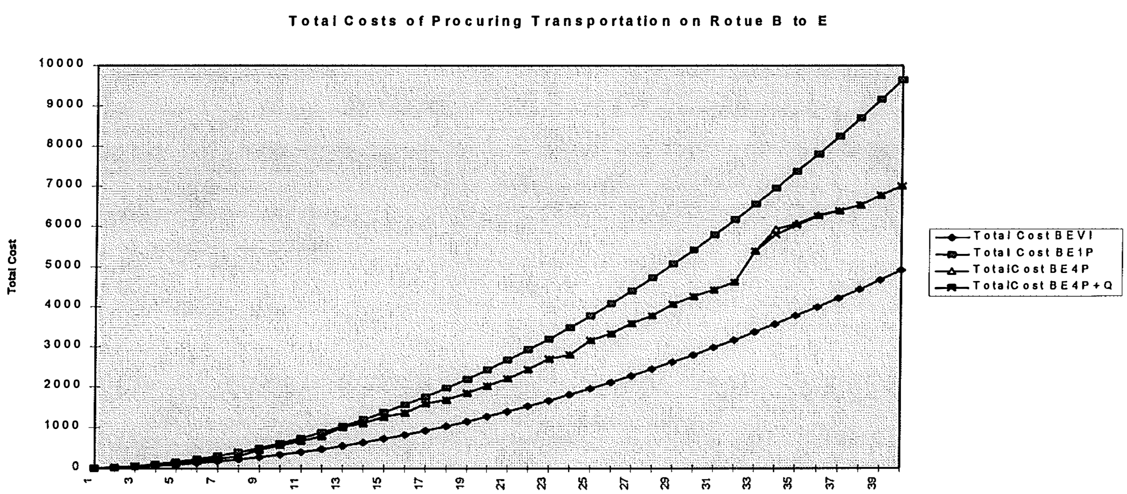
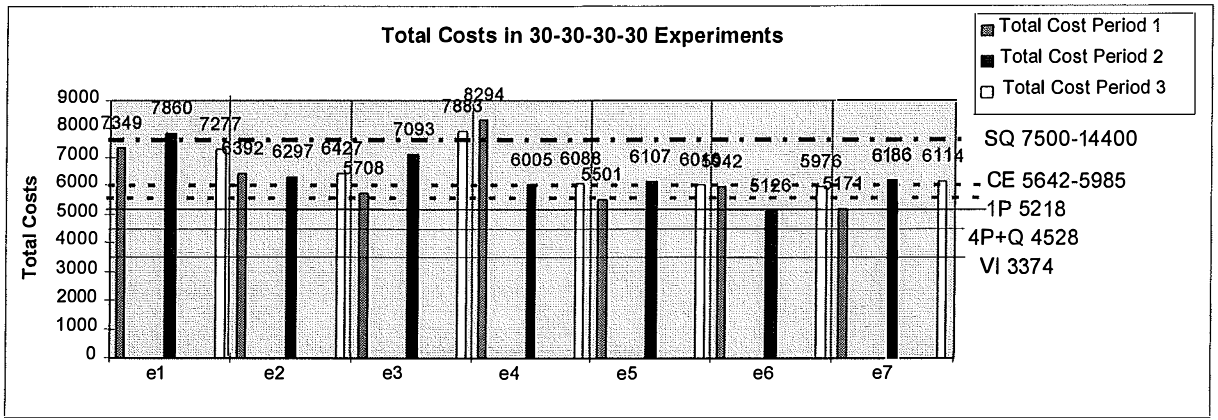


Figure 7. Comparison of principal's observed total costs with theoretical benchmarks



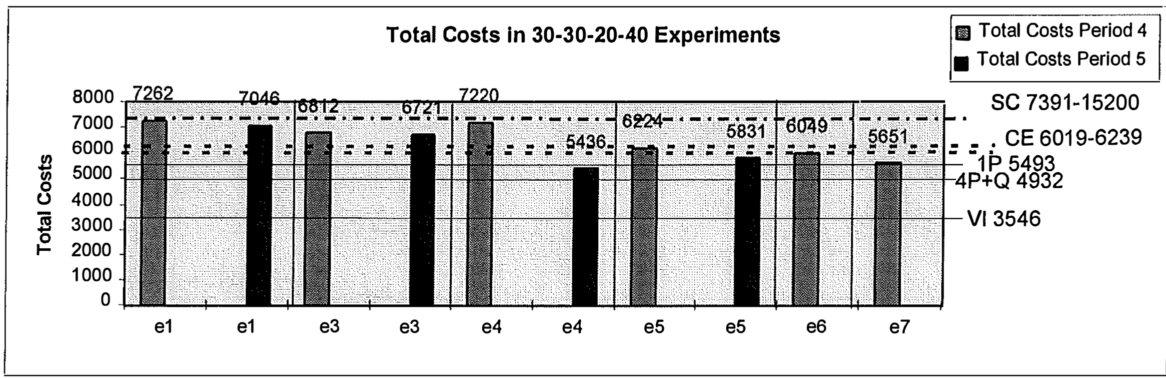
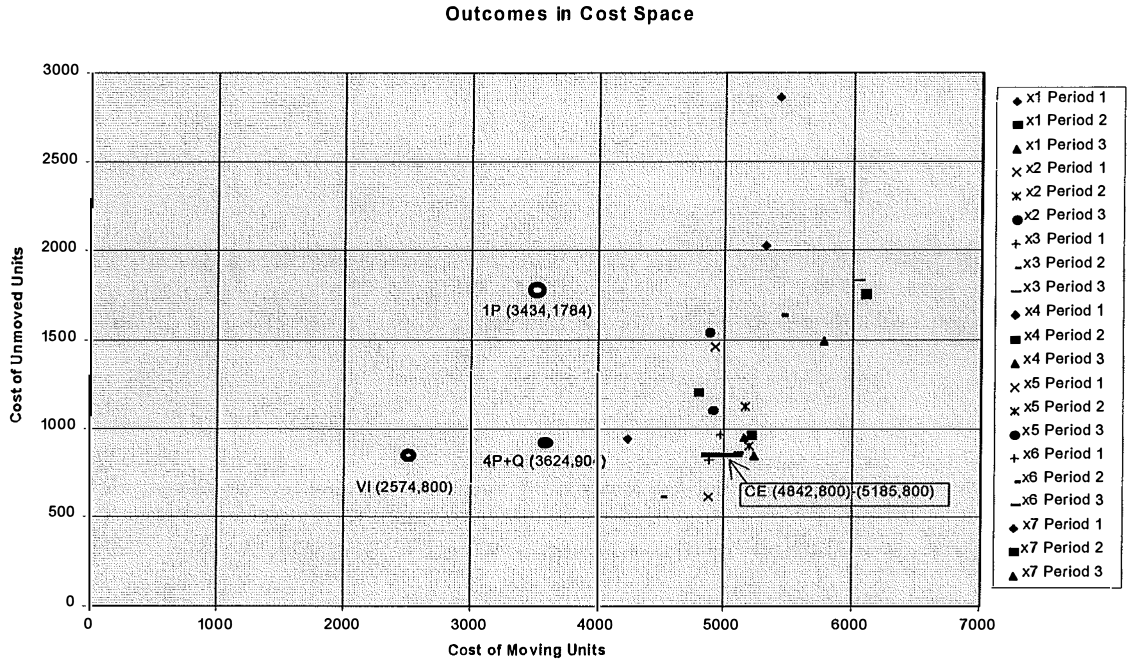
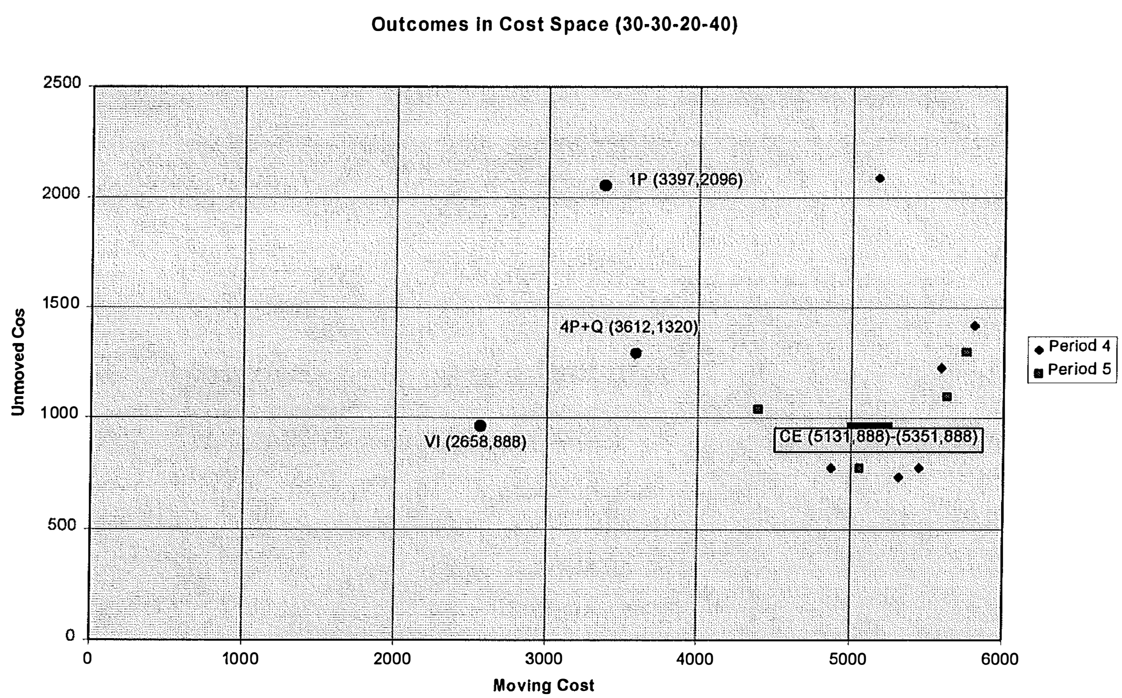


Figure 8A. Comparison of observed cost tradeoffs achieved in the experiments with theoretical benchmarks. M_T=(30,30,30,30)



Note: SC Benchmark is off scale at lower right. It would be a line segment of possibilities from (7396,104) to (14296,104).

Figure 8B. Comparison of observed cost tradeoffs achieved in the experiments with theoretical benchmarks. M_T=(30,30,20,40)



Note: SC benchmark is off scale to lower right. It would be a line segment of possibilities extending from (7311,80) to (15120,80).