Implementation of a Combinatorial Market. The Experiments Behind the Automated-Environmental Credit Exchange (ACE)

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1 Introduction

While a number of economists have advocated the use of combinatorial (*i.e.*, complex package and contingent bidding) market mechanisms (*e.g.*, Ledyard, Plott, Porter, Smith), they have not been widely used. Arguments against such markets point to the computational complexity of finding an allocation and the difficulty bidders may have to understand a relatively complicated market mechanism. In this paper we outline the design and implementation of a complex combinatorial market to trade pollution credits. This market is innovative not only for its use of complex bids, but for the use of the inter-net as a bid submission medium, and that it is direct competition with other market mechanisms for the trade of pollution permits. The design and implementation of this market mechanism used the ideas and lessons learned from experimental markets and used experimental methodology to test the market mechanism.

The market mechanism was designed to facilitate trades made under Coast Air Quality Management District (SCAQMD) in the fall of 1993 (in the area surrounding Los Angeles, California, one of the most polluted cities in the USA). RECLAIM enables large companies to meet their pollution-reduction targets either by installing new equipment or by purchasing pollution credits from other participants who have met their pollution-reduction goals.

In order for a pollution-market to be effective it is important to have trading mechanisms that allow efficient trading and give information on pricing for future planning. Until our implementation the Automated-Environmental Credit Exchange (ACE), most trades were brokered. Polluters who wished to buy or sell pollution credits either tried to find partners for their trades or contacted brokers who attempted to find matching buyers or sellers. One other alternative was offered by the brokerage firm Cantor-Fitzgerald who offered a sealed-bid and -offer auction; this auction supplied little price information or other market feedback to the participants.

A first solution might be to construct a simple two-sided market for each RTC, but there are at least two important reasons why brokered or simple (single asset) market mechanisms may not be efficient in the pollution credit market. Because of the thinness and newness of the market there was very little market information for the bidders to act on, so bidders where highly reliant on the brokers for price information. But most importantly there may exist synergies (returns to scale) between different pollution assets. One of the goals of ACE is to allow more trading by increasing price information to the polluters and by allowing complex and flexible bids and ask to increase the number of trades.

While there are many aspects to this problem, in this paper we will focus on the experiments we used to design the ACE market mechanism. We first give some background on the RECLAIM program. We then provide a brief overview on some of the market properties that make the RTC market both unique and difficult. Some experimental background, the design of the experiments and the experimental results are then provided. We next give an overall description of the market mechanism we designed, its experimental testing. We end with some results of the actual implementation of the market mechanism and some concluding remarks.

2 Brief description of the RECLAIM program

On October 15, 1993, the South Coast Air Quality Management District (SCAQMD), the geographical area around Los Angeles, California, adopted the country's first set of market-based air pollution incentive rules, which it called the Regional Clean Air Incentive Market (RECLAIM). RECLAIM is a market-based program that mandates reductions in emissions of nitrogen oxide (NOx) and sulfur oxide (SOx) by imposing factory mass emissions' caps. Under RECLAIM, a manufacturer is given an annual emissions limit for its entire plant, and yearly reductions to the plant-wide limit. A factory emitting less than its allocation cap is permitted to sell its excess emissions to other facilities in the form of RECLAIM Trading Credits ("RTCs"). If a factory finds that it will emit more than its cap, it may either purchase RTCs from other facilities or make reductions in emissions by either installing control equipment or reducing production.

There are about 400 companies covered in the RECLAIM program. They have been given annual allocations of NOx and SOx for the years 1994 through 2003. These allocations are based on peak production levels from 1989 through 1994 and mandated emission restrictions. The RECLAIM program divides facilities into 2 compliance cycles and 2 geographic zones, The first compliance cycle issues annual allocations for January 1 to December 31 of each year. The second compliance cycle issues annual allocations for July 1 of each year to June 30 of the following year. Historic weather patterns and geographic features define the coastal and inland zones. Each RTC is valid for the single year cycle and zone for which it was issued.

Facilities may purchase and use RTCs for the other compliance cycle as long as they cover emissions that occur prior to the RTCs expiration (emissions are reported monthly). RECLAIM facilities that violate their annual emissions cap risk losing their factory permit and are subject to a maximum penalty of $1,000 per day. RECLAIM provides companies the flexibility to make more cost-effective emission reductions than was possible under a command-and-control program. However, RECLAIM does not establish a mechanism for the trading of RTCs, it only establishes a marketable asset or property right. If trading pollution credits is to be a viable form of efficient pollution control there must be an efficient method of trading RTCs.

3 Difficulties with a RTC market

The goal of the ACE market is to provide a method of trade for the participants of the RECLAIM program. Prior to the ACE market, trading was accomplished by posting bids and asks on a public electronic bulletin board set up by the SCAQMD, indivdiually searching for matching sellers or buyers, or through a permit broker. Some of the participants in RECLAIM were concerned that these methods were inadequate to meet their needs, and that there was a need for a better trading mechanism. This lead to a market mechanism that was designed to fit the trading needs of the participants.

Under RECLAIM there are a large number of different RTCs. There are two basic pollutants (NOx and SOx), two geographic zones (coastal and inland), two cycles and 18 six month time segments (as of January 94), for a total of 144 different RTCs. Trading in this number of different RTCs is a tedious task, but a complicating feature of the RTC environment is that firms may wish to obtain or sell multiple RTCs of fixed size or packages of different RTCs. This is because of the synergies and non-convexitites that may exist. The synergies arise from economies of scale and scope resulting from the ownership of polluting abatement equipment. Non-convexities arise because some trades must be made in their entirety or not at all.

For example, a firm's production plans require it to emit 1 million pounds of NOx per year for 5 years using current technology. If the firm has a 800,000 pound cap on NOx emissions it will not be able to meet its production goals and stay within its environmental constraints. To meet these goals the firm may have a number of options:

- Purchase pollution abatement equipment which will reduce 200,000 pounds of NOx per year for 1 million dollars.
- Purchase 200,000 RTCs for each of the 5 years.
- Purchase 100,000 RTCs for each of the 5 years and purchase pollution abatement equipment which will reduce 100,000 pounds of NOx per year for 600,000 dollars.
- Trade current year RTCs for future RTCs (switching production).

The option that is most cost effective for the firm will depend on the cost of RTCs. The firm would like to be able to purchase 5 years RTC as one package. If the firm were to purchase the first year credits and then find that the prices of the last year credits exceed the cost of the investment in equipment, the firm might find that it has not acted in the most cost-effective way.

A second feature of pollution permits is that the demand for RTCs could be superadditive or "lumpy", that is, 100,000 RTCs in one year could have much more value to this firm than 50,000 RTCs in two years. To another firm 50,000 RTCs in two years may have more value than 100,000 RTCs in one year.

A number of researchers made earlier explorations of similar problems. For example, Grether, Isaac, and Plott (1979) and Rassenti, Smith and Bulfin (1982), studied the the allocation of airport landing slots and Banks, Ledyard and Porter (1989) studied the allocation of services on NASA's planned earth-orbiting Space Station Freedom. In the airport slot allocation problem, scheduled flight patterns require airport slots to be packaged in fixed combinations, a slot has value only in combination with other slots, so it was desirable to have a primary auction in which airlines submit package bids. In addition, there may be a number of flight patterns that would supply the same objective. Rassenti, Smith and Bulfin (RSB) proposed a computer algorithm to solve the set packing problem which maximizes the total value (economic welfare or surplus) as revealed in the bids submitted, subject to resource and contingency constraints.

The mechanism provided by RSB was a one slot sealed bid auction. Banks, Ledyard and Porter (1989) designed a mechanism they called AUSM which allowed bidders to update their bids. More recently, McCabe, Rassenti and Smith (1989) have examined the transportation of gas in a network, Brewer and Plott (1996) and Cox, Offerman, Olson, and Schram (1998) have examined the allocation of railroad tracks. Porter and Rangell (1993) describe a computer assisted resource exchange for NASAs Cassini mission to Saturn. In addition, there has been much discussion of the auction of radio frequencies by the Federal Communications Commission (*e.g.*, Bykowsky, Cull and Ledyard (1995)).

Our problem is slightly more complicated. In the RECLAIM market there are both buyers and sellers, demands are multi-unit, and there should not be any surplus revenue excess of transaction fees. The RTC market has the features of thin trading, convexities, synergies, a lack of price history and the need for price discovery (firms wanted reliable price information for planning purposes), firms desire for swaps and flexibility, and defaults must be prevented.

Almost all of the literature examining this problem uses experimental testbedding (see Ledyard, Plott). We followed much of the same approach.

4 Experimental Tests

We knew that a successful RTC trading mechanism would need to be robust to its environment. However, we did not know if traditional market mechanisms like double auction (NYSE) or a single-call call market would work well under this environment or if these trading mechanisms would be able to adequately meet our goals, or if we would need an entirely new type of market mechanism. Given (where xx) our goals and the constraints of the environment, we wanted to know what market mechanism would work "best". The problem we attempt to solve is unique and we knew of no existing mechanism with field experience. The experimental literature provides two classes of mechanisms: two-sided simultaneous single good markets such as the double auction as used in the New York Stock Exchange, call markets as used in the Arizona Stock Exchange, and Walrasian tatonnement mechanisms (see Porter and Rangel). Single sided combinatorial auctions; such as AUSM and RSB were designed for markets with combinations and convex preferences similar to the preferences in the RTC environment, however providing two-sided variations required significant development.

Of the previously tested mechanisms an uniform price call market is known to work well and had many of the features that we required for the RTC market. It had the advantage of giving a single price and high efficiencies in markets without complexities. In an asset market environment, Liu (1992), Van Boening *et al.* (1992), Friedman (1993) found that the allocative efficiency of a call market was not significantly different from that of a continuous double auction. Smith *et al.* (1982) found the double auction had an average efficiency of 94 percent compared with 92 percent of the sealed-bid call market; and the implementation of an unanimity rule increased efficiencies of the sealed-bid call when unanimity was reached.

Since the call market has a uniform single price, it lacks the price volatility of the double auction. The bidders have less opportunity to be influential on the final price, and there is less of a need to be strategic, except for those bids at the margin which influence the price. This makes bidding simpler for the participants once this is realized (as is the case of the second price auction, this is not always so evident to the participants).

Experience with AUSM of Banks *et al.* and the UPDA mechanism of McCabe *et al.* (1993) has shown that allowing the bidders to update their bids would improve the allocation. We instituted an iterative version of the call market. In complex environments, past experience has shown that iterations with some sort of commitment is needed to stabilize response and to speed convergence. It allows feedback, reaction, and learning about the possibilities. In previous experimental tests the iterative call market was shown to perform well and had good revelation qualities (see Banks, Ledyard, and Porter (1989)).

Simply, the iterative call market is a two-sided market for a single commodity, that accepts bids and asks which consist of a quantity and a price. Bidders are allowed a fixed time interval to place their bids. At the close of the round, bids are sorted from high to low and asks are sorted from low to high. This forms the classical supply and demand curves. The intersection of the curves determines a tentative price and quantity. See Davis and Holt (1993) for an discussion on sealed-bid call markets.

Because of the discreteness of the quantities, there may be more than one price that would satisfy the competitive criteria. We must choose one, the midpoint of the competitive region. More formally, the market price of the traded units is

$$P = (P_L + P_H)/2,$$

where,

$$P_H = \min(\text{accepted bids, rejected asks}),$$

and

$$P_L = \max(\text{accepted asks, rejected bids}).$$

This tentative price and quantity and whether the bid was provisionally accepted is then reported back to the subjects. The subjects were then allowed to submit new bids or offers. If a subjects bid or offer was tentatively accepted in the last round it could not be removed (it was automatically resubmitted by the experiment computer). Rejected bids and offers were not required to be re-submitted. The market closed when there were no new bids or the quantity transacted did not increase between rounds.

Our initial experimental tests were designed to answer the question: If we do not allow complex bids, in our complex environment, what are the properties of the "best" existing mechanism. To test the mechanism we examine a number of environments, representing characteristics that may exist in the RTC market. We conducted a number of experimental sessions with different environments (induced preferences and endowments) which attempt to capture the features of the RTC environment. We report on a subset of these sessions which we consider to have significant information.

Three items are important in measuring the effectiveness of a market mechanism. 1) The overall efficiency, 2) the nearness to the competitive equilibria (if one exists), and 3) the revelation properties of the mechanism. It is possible that a mechanism may obtain one objective but not the others. The welfare measure used in this study to compare the allocations in our various treatments is the percentage of the maximum possible gains from trade which is realized by the allocation process. This fraction is called the *efficiency* of the allocation. It is computed as the sum of the producer and consumer surplus (producer surplus is the revenue to the auctioneer) resulting from the allocation process divided by the sum of the producer and consumer surplus occurring in the competitive equilibrium. This measure has been used extensively in previous studies including many of those mentioned in this section.

4.1 Experimental Procedures

Subjects were recruited from the undergraduate student population at the California Institute of Technology. All the experimental had experience in other markets experiments and practice in a non-paying session of the iterative sealed-bid mechanism. Each experimental session consisted of a single market instance. Each session was run on a computer network. Experimental sessions consisted of 3 markets traded simultaneously. Subjects were assigned randomly to sets of redemption values and costs and endowments.

Subjects' valuations and costs were provided in terms of the experimental currency, francs. The subjects were told the conversion rate, which was the same for each market and subject, before the start of the experiment. All subjects were paid in cash at the end of the experimental sessions.

Communication between subjects was not allowed during the experiment. It was common information that each subject knew his own valuations or costs and endowments, but nothing about the valuations, costs, or endowments of his competitors. Each subject knew the maximum number of competitors in each market but not the number of subjects who had valuations or costs (a subject could have valuations or costs in only one or two of the markets). Furthermore, if the auctioneer placed units for sale, each subject knew how many items were for sale. All of this information could be found in the instructions, which were read aloud at the beginning of the sessions. They are available from the authors.

Each experimental session consisted of a single market period consisting of a sequence of rounds or iterations. Each subject had 3 minutes to enter bids and asks and had a limit of 4 bids or asks in each round. At the beginning of each round and after the first round, the current market price and the number of units tentatively accepted for trading in each market are displayed on the computer terminal. This information was available for all the past rounds.

One important point to note about the experimental design. Since the RTC market is relatively new and most potential participants were novices and had little or no information about the environment. We felt it was important to judge the performance of the mechanisms using only a single realization of the market. We did not repeat periods, which is common in many experimental tests on markets. We were interested in how the markets would operate in the short run, when participants had little knowledge. We were not interested in the long run results, which may be observed with replication of the same economic environment and market mechanism.

Market	A		B		C	
	Demand	Supply	Demand	Supply	Demand	Supply
	4 @ 75	7 @ 15	4 @ 100	0	10 @ 15	4 @ 10
	3 @ 50		3 @ 50			6 @ 20
	6 @ 40		6 @ 40			3 @ 35
			3 @ 25			
			1 @ 10			
Price	50		NA		15	
Quantity	7		NA		4	
Welfare	345		NA		20	

Table 1: *Redemption values (demand) and costs (supply) for the simple environment. Including the competitive price and quantity and maximum possible welfare.*

4.2 Experimental sessions 17 and 24

The first environment is the simple environment. It consisted of 3 independent homogeneous goods (A, B, and C), and six subjects with multi-unit preferences for each good. There are no block, or super/sub additive preferences, The three goods are traded simultaneously but separately in its own market. Market A and C are similar to environments that have been replicated numerous times for a homogeneous good (see Davis and Holt (1993), and Friedman (1993)). These three markets could be considered to be “thin”, that is, they have a small number of participants and diverse preferences.

In market A there was a single supplier with no supply competition at the margin. In market B there was no supply of the good (this is not known to the subjects), a condition that is likely to occur in the RTC market for some of the RTCs. In market C there was a single demander with excess demand at the competitive price. Table 1 shows the aggregate demand and supply and the equilibrium quantity and price for each market.

Two experimental sessions were run, labeled 17 and 24. Session 17 required 7 rounds to close and session 24 required 5 rounds to close. Table 2 and Table 3 present the round by round results of market A and C.

Except for session 17 of market A, efficiencies were low; and except for session 24 of market A, where a subject lost money, the quantity traded was below the competitive equilibrium quantity. Because the potential for profit was low in market C, perhaps subjects provided less effort to increase

	Session 17			Session 24		
Round	Price	Quantity	Efficiency	Price	Quantity	Efficiency
1	-	0	0	-	0	0
2	30	2	42%	40	1	21%
3	31	2	42%	40	3	42%
4	34	3	54%	40	5	84%
5	35	5	72%	40	5	75%
6	37	5	72%			
7	38	6	96%			

Table 2: *Results market A, simple environment, sessions 17 and 24.*

	Session 17			Session 24		
Round	Price	Quantity	Efficiency	Price	Quantity	Efficiency
1	-	-	-	10	2	50%
2	-	-	-	10	2	50%
3	-	-	-	10	2	50%
4	-	-	-	10	3	75%
5	-	-	-	10	3	75%
6	28.5	2	50%			
7	28.5	2	50%			

Table 3: *Results market C, simple environment, sessions 17 and 24.*

trades. Since there was not any replication of environment subjects had no opportunity to learn the parameters of the environment. This lack of knowledge is likely to exist, at least initially, in the RTC market, since there is no previous experience in trading these pollution permits.

4.3 Experimental session 34

In the environment for session 34, demanders had superadditive redemption values (*i.e.*, Value(unit 1 and unit 2) > Value(unit 1) plus Value(unit 2)). It describes the case where firms require a block of trading permits (over time or units). In this session there were 8 subjects and 3 markets (A, B, and C). Some subjects had increasing marginal values (superadditive) for units and no endowment of units, the remaining subjects had decreasing marginal values and endowments of units (providing for an increasing marginal cost of selling units). For example, trader 5 in market B has an endowment of 3 units, if he sells a single unit his opportunity cost is 18, the second unit he sells has an opportunity cost of 21, if instead he acquires a 4th unit he receives a value of 7. The values for this session are listed in Table 4

In markets A and B there were gains from trade available for both buyers and sellers. In market C, none of the subjects were given endowments, instead the auctioneer offered a fixed supply of 10 units at a price of $0.10 for each unit. Competitive equilibria exist for markets A and B but not for market C. Table 5 gives the market conditions, and Table 6 and Table 7 gives the results of the session.

Session 34 required 7 rounds to finalize the allocation. The final efficiencies were 78.6, 82.5, and 98.5 percent. The high efficiency of market C indicates that the non-existence of competitive equilibrium does not always result in a likelihood of low efficiencies. In market C, the selling price was $0.10, so there is a known range of acceptable prices (anything greater than $0.10), where in markets A and B both sides of the market had to find the acceptable price range. In market C, the low variation of subject valuations resulted in that any allocation of 10 units will yield relatively high efficiencies.

Market A had the lowest final efficiencies. In market B, the maximum buy price was lower than the minimum sell price for the first 4 rounds. In this market there was a much smaller price range in which trades could be profitable, once prices reached this range there is little variation in allocative efficiency. The iterative sealed bid auction seems to work better if the equilibrium price range is large. In market C there is a lot of allocation switching between the rounds.

	Subjects							
	1	2	3	4	5	6	7	8
Market A								
Endowment	0	0	0	0	0	5	5	5
Unit 1	20*	20*	20 *	20*	20*	15	15	15
Unit 2	35*	30*	30*	25*	20*	12	12	12
Unit 3	45*	40*	35*	30*	25*	11	11	11
Unit 4	0	0	0	0	0	0	0	0
Unit 5	0	0	0	0	0	0	0	0
Market B								
Endowment	0	0	0	0	3	3	2	2
Unit 1	27*	13	7	5	25	25	25	27
Unit 2	28*	15	10	9	21	19	13	15
Unit 3	29*	17	13	13	18	17	10	10
Unit 4	30*	19	16	17	7	7	7	7
Unit 5	31*	21	19	21	5	5	5	5
Unit 6	32*	23	21	25	0	0	0	0
Unit 7	33*	25	24	29	0	0	0	0
Unit 8	34*	27	27	33	0	0	0	0
Unit 9	35*	29	30	37	0	0	0	0
Unit 10	36*	31	33	40	0	0	0	0
Market C								
Endowment	0	0	0	0	0	0	0	0
Unit 1	35*	35	35	30	30	50*	50*	50*
Unit 2	60	60	60	55	55	58*	58*	58*
Unit 3	65	65	65	60	60	60*	60*	60*

Table 4: *Redemption values and endowments for the Super 1 environment. The welfare maximizing allocation is marked with an *.*

Market	Competitive Quantity	Competitive Price	Max Welfare	No Trade Welfare
A	15	[12.67,21.66]	415	114
B	10	?	315	205
C	-	-	539	0

Table 5: *Session 34 market conditions.*

Market	Allocated Quantity	Final Price	Final Market Efficiency
A	9	20.5	78.6%
B	6	25	82.5
C	10	39.9	98.5

Table 6: *Session 34 final results.*

Round	Price			Quantity			Efficiency%		
	A	B	C	A	B	C	A	B	C
1	10	-	20	2	-	10	39.5		
2	15	-	21	2	-	10	39.5		
3	16	-	25.1	4	-	10	52.8		
4	19.9	-	30	6	-	10	67.7		
5	20	-	32	6	-	10	60.5		
6	21	22.5	35	7	1	10	65.3	69.5	
7	20.5	25	39.9	9	6	10	78.6	82.5	98.5

Table 7: *Observed price, quantity, and efficiency for session 34 in each market (A, B, and C) by round.*

4.4 Experimental sessions 18 and 25

Experimental sessions 18 and 25 were designed to be the most difficult environments for the uniform price call market to achieve efficiencies. Markets A and B comprise the AUSM environment, and market C comprises the Tak environment. The AUSM environment involves two goods, A and B, each with a fixed supply of 20 offered by the auctioneer for a cost of \$0.10 per unit. There were 6 bidders with valuations which required that they acquire both goods A and B to obtain valuations. Each subject was given 9 possible choices and any excess units had no value to the subjects, see Table 8. For more detail on AUSM see Banks, Ledyard, and Porter (1989).

In the Tak environment (market C) subjects had valuations for a single good. Two of the subjects had inflexible demands, that is, they had to obtain a fixed number of units to receive any value, less than that amount or any additional units had no value to the subjects, see Table 9. This market has no competitive equilibrium price.

We ran 2 experimental sessions, labeled 18 and 25. Final efficiencies for the AUSM environment were 65.4 and 53.8 percent. Efficiency did not increase with after each round. In 9 opportunities efficiency decreased between rounds 4 times. In the Tak environment there was never any allocation.

Another poor feature was that there was a tendency for subjects to overbuy. See Table 11, which gives the number of units purchased in the A and B markets that had a redemption value of 0. For example, to receive value from any allocation in the AUSM environment subjects had to purchase units of both A and B. If a subject purchased 9 unit of A and no units of B then he has overbought 9 units of A. Also if a subject has a redemption value for 9 units of A and 5 units of B, and 13 units of A and 7 units of B, but was only able to purchase 10 units of A and 6 units of B, then he overbought 1 unit of A and 1 unit of B since he receives the same value for (10 units of A and 6 units of B) as for (9 units of A and 5 units of B).

5 The approach to the ACE market mechanism

The failure of the iterative call market to provide adequate clearing of markets when convexities and synergies existed, convinced us that new market design was necessary. We were able to use the experience of these experiments and the experience of past experiments to complete the design of a simultaneous market mechanism with combinatorial bidding. We wanted a mechanism that provided efficiency, allowed more trading, anonymity of bidders, useful price information, outcomes that were considered “fair” by

Bidder ID	A	B	Redemption Value	Bidder ID	A	B	Redemption Value
1	4	3	100	2*	3	6	125
1	7	3	175	2	3	10	150
1	12	3	250	2	3	14	175
1	4	9	150	2	9	6	175
1	7	9	225	2	9	10	190
1*	12	9	325	2	9	14	200
1	4	13	175	2	15	6	200
1	7	13	250	2	15	10	225
1	12	13	335	2	15	14	250
3	3	2	75	4	6	8	100
3	3	4	100	4	6	10	150
3	3	9	125	4	6	12	200
3	5	2	100	4	8	8	150
3*	5	4	200	4	8	10	200
3	5	9	225	4	8	12	275
3	12	2	175	4	12	8	175
3	12	4	250	4	12	10	250
3	12	9	275	4	12	12	300
5	6	7	175	6	7	7	75
5	6	10	225	6	7	9	150
5	6	13	250	6	7	11	175
5	9	7	225	6	9	7	125
5	9	10	275	6	9	9	175
5	9	13	300	6	9	11	200
5	12	7	250	6	11	7	150
5	12	10	300	6	11	9	200
5	12	13	325	6	11	11	225

Table 8: *AUSM Redemption Values, welfare maximum = 650, * indicates the optimal allocation.*

Buyers	Type	Value
B1	inflexible	5 units for 350
B2	flexible	2 units for 80
B3	flexible	4 units for 120
Sellers		
S1	flexible	3 units for 150
S2	inflexible	2 units for 160
S3	flexible	2 units for 180

Table 9: *Tak Environment, Market C, 3 buyers 3 sellers, Optimal allocation B1, S1, S2 welfare* $= 350 - 310 = 40$

	session 25					session 18				
round	Eff	P_A	P_B	Q_A	Q_B	Eff	P_A	P_B	Q_A	Q_B
1	65.4	1.0	0.1	20	18	46.2	5	2.	20	20
2	88.5	5.0	5.0	20	20	26.9	10	4	20	20
3	65.4	5.0	5.0	20	20	53.8	10.5	5.2	20	20
4						61.5	11.2	7.5	20	20
5						34.6	15.	8.0	20	20
6						76.9	15.2	9.0	20	20
7						46.2	16.5	10.	20	20
8						53.8	16.7	10.1	20	20

Table 10: *Results session 18 and 25 call market, AUSM environment (market A and B), no allocations market C.*

	session 25					session 18				
round	sA	sB	oA	oB	Rev	sA	sB	oA	oB	Rev
1	324.0	255.2	6	7	579.2	160.0	101.0	6	7	261
2	358.0	337.0	2	-	695	265.0	101.0	8	18	
3	360.0	359.5	6	9	719.5	284.0	175.0	12	5	
4						292.0	175.0	5	5	467
5						321.8	175.0	11	11	496.8
6						333.6	183.0	2	1	516.6
7						347.3	200.0	11	7	
8						353.6	223.0	12	5	576.6

Table 11: Results session 18 and 25, observed surplus (sA and sB), overbought quantities (oA and oB) and revenue (Rev), by round.

participants and had the bid forms and flexibility that the customers wanted.

Our goal of the market mechanism was 1) to select and complete the set of trades that maximizes traders' true surplus (this minimizes the necessity for an aftermarket and is Pareto-optimal assuming quasi-linear preferences), 2) to charge everyone a price that leaves them at least as well off as if they did not participate, that is seen as "fair" by the participants (one part of fair is that everyone pays the same per unit price if that is possible) and 3) does not require the auctioneer to spend any of her own money nor extracts any surplus from the traders. If it exists, a competitive equilibrium is exactly what we are looking for.

Previous experimental evidence suggested a once and only submission of bids will not find anything near the surplus maximizing outcome, so we proposed an iterative procedure with a stopping rule that we believed would encourage participation early. Further, if we can do this so that there are strong incentives for traders to reveal their true values, then the surplus maximizing outcome may be realized.

To do all this, the mechanism must at each iteration, take the collection of proposed trades (bids and asks), find the surplus maximizing allocation, and find charges for each trader that satisfy the appropriate constraints. It must do this in a way that is reasonable if we were to stop and that provides the right incentives to traders if we don't stop. This assumes that reports are "honest" and sufficiently "rich" (that is, these are among the best that any agent has a feasible chance of completing) and that solving that maximization problem finds the surplus maximizing trades.

We have divided the mechanism into two parts for descriptive purposes. The first is the allocation problem and the second is the pricing problem. The allocation problem is conceptually simpler but computationally more complex (in that it is more computer intensive and time consuming), while the pricing problem is conceptually more difficult but computationally simpler, because of the possibility that competitive prices do not exist.

5.1 The general outline of the mechanism

The mechanism, which we call the "G" mechanism, is structured as an iterative sealed bid. Prior to the auction bidders must place into escrow an amount of money and RTCs. The escrow amount places restrictions on the bids and asks, which reduces the likelihood of a default. At each round (iteration) agents submit buy/sell orders; a tentative allocation is made that maximizes welfare (the sum of seller and buyer surplus). Winning orders are automatically entered into the next round and can only be replaced if a new allocation improves welfare. This adds commitment to the bids and should lead to an increasing value of total welfare. Bidders can update an accepted order by increasing a buy bid, decreasing a sell ask, increasing flexibility, or by including the accepted bid in a contingent order. Bidders can modify rejected bids in any manner, they are not automatically entered in the next round. If welfare does not increase by 2 percent after round 3 or round 4 the market ends and transactions are made based on the allocation of the last round. There is a maximum of 5 rounds and a minimum of 3 rounds.

Conceptually the allocation problem takes submitted bids and maximizes welfare given demand and supply constraints and contingent constraints. This is a mixed integer linear programming problem (MILP) and there are many techniques to solve this type of problem (we will not discuss the details). The basic problem is that with 124 different RTCs and a large number of bids computation may take a large amount of time. For our initial ACE market we broke the RTCs into four smaller markets NOx zone 1, NOx zone 2, SOx zone 1, SOx zone 2; each one of these submarkets has 33 RTCs. With a large number of bids and a large number of contingent bids this could still be computationally time consuming. Because of this, it was important to specify allowable bids that retained the packaging and contingent capabilities but also reduced the computational burden.

There are four immediate problems. 1) What is the structure of allowable bids? 2) How do we determine which bids and offers to accept, and how do we accomplish this in a reasonable amount of time? 3) What information is given to the agents between rounds? 4) How are prices computed and what do the agents pay?

Prices need to be determined so that 1) revenues (ignoring transaction fees) sum to zero. 2) No-one pays more or receives less than they ask including transaction fees. 3) There are incentives to reveal and to be flexible. 4) The process is computable in a reasonable amount of time and 5) It can be explained in a reasonable manner.

The information supplied between rounds must be useful for updating bids and preserve the confidentiality of bidders. The forms of the bids must allow the synergies or returns to scale to be exploited and the allocation problem must be computable.

The allocation and pricing procedures are described separately, but first we describe the types of orders[1] that were allowed.

5.2 Simple orders

A simple order for agent i is $< b_i, x_{i1}, \ldots, x_{ik}, F_i >$ where:

- $b_i > 0$ means, agent i will pay at most b_i,
- $b_i < 0$ means, agent i wants to receive at least b_i.
- $x_{ik} > 0$ means, agent i wants to get x_{ik} units of k,
- $x_{ik} < 0$ means, agent i will deliver $-x_{ik}$ units of k.
- F_i is a scale factor $(0 \leq F_i \leq 1)$ which indicates that agent i is willing to buy or sell any amount between $< F_i \cdot b_i, F_i \cdot x_i >$ and $< b_i, x_i >$.

For example, an order $< 1000, (0, 0, 10), 0.6 >$ indicates that the agent is willing to purchase any size order between the full size and 60 percent of the full order. That is, he is willing to pay up to \$1000 for 10 units of asset 3. He is also willing to pay up to \$600 for 6 units of asset 3 or any convex combination of these orders. If $F_i = 1$, then the agent is totally inflexible, and if $F_i = 0$, then the agent is totally flexible. As we will see, inflexibility will come at a cost to the agent.

5.3 Complex and package orders

Orders may be packaged, that is, an order may consist of a number of buy or sell assets. For example, I am willing to pay up to \$100 for 10 units of

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[1] We use the generic term ('order') for bids to buy, offers to sell, and any packaged combination.

asset 2, pay \$50 for 20 units of asset 3 and 30 units of asset 4. A package order may also consist of a swap, which consists of buying units of some assets and selling units of other assets. For example, I am willing to pay up to \$10 and supply 10 units of asset 4 only if I receive 10 units of asset 2.

Orders may also be connected by logical ORs (also called contingent bids). An OR is a logical element that binds one or more orders together. Only one order of a set orders that is ORed together can be transacted. The order that will be transacted is the order that maximizes market welfare, as will be described below. That is, an agent is able to submit an order that states he is willing to purchase 10 units of asset 3 for up to \$10 if and only if he is not able to purchase 20 units of asset 4 for up to \$20. This is equivalent to saying, out of this set of orders I only want to allocated a single order.

5.4 The market Allocation

The allocation at each round is determined to maximize welfare (V^*) over the submitted orders. Formally,

$$V^* = MAX_{d_i} \sum_i b_i * d_i \tag{1}$$

subject to:
(1) Feasibility,

$$d_i = 0 \quad \text{or} \quad F_i \leq d_i \leq 1. \tag{2}$$

(2) Market constraints,

$$\sum_i d_i * x_{ik} \leq 0, \quad \text{for all RTCs } k. \tag{3}$$

(3) Logical constraints,

$$\sum_{j \in M_i} \delta(d_j) \leq 1, \quad \text{for all logical sets } M_i. \tag{4}$$

(4) Positive welfare,

$$V^* > 0. \tag{5}$$

The constraints (1) indicates a feasible allocation, if $d_i = 0$ then order i is not allocated and if $F_i \leq d_i \leq 1$ then order i is allocated at scale d_i. If $F_i = 1$, then d_i can only take on the values 0 or 1. The constraints (2) maintain that demand shall not exceed supply for an asset. The constraints (3) maintain that only one order of a logical set may be allocated, where $\delta(x) = 1 \quad \text{if} \quad x \geq 0, \quad \delta(x) = 0 \quad \text{if} \quad x = 0$. The constraint (4) allows only total allocations with a positive welfare, if $V^* \leq 0$ then there is no allocation.

5.5 Pricing

The pricing problem addresses the problem of how to charge the buyers and pay the sellers. The competitive equilibrium prices fulfill the requirements on prices stated above, so we first attempt to find a competitive equilibrium, if it exists. After the allocation problem is solved there are three types of bids; those that were accepted by the allocation, those that were rejected by the allocation but were not part of a logical OR set with an accepted bid, and those bids that where rejected and were part of a logical OR set with an accepted bid. If a competitive equilibrium price p exists it would satisfy:

$$\begin{aligned} b_i - p'x_i &\geq 0 \quad \text{for all accepted bids,} \\ b_i - p'x_i &\leq 0 \quad \text{for all rejected bids,} \\ b_{ij} - p'x_{ij} &\geq b_{ij^*} - p'x_{ij^*}, \\ & \quad \text{if } ij \text{ is an accepted bid and } ij^* \text{ is part of the} \\ & \quad \text{logical OR set that contains } ij, \\ & \quad \text{and} \\ p' \sum_{i \in A} x_i &= 0 \qquad \text{Walras' law.} \end{aligned}$$

The first three conditions state that prices are such that each accepted bid is positively valued and each rejected bid is negatively valued, the fourth condition is Walras' law. If one such p exists, there may be many of them so we must select one. We use the following method: Find the competitive equilibrium price that maximizes the net surplus to the buyers (this will be a set of "low" prices), then find the competitive equilibrium price that maximizes the net surplus to the sellers (a "high" price), and then, finally, take a 50-50 average of the two prices. All three will be competitive equilibria but the last has some claim to be symmetric and "fair".

If there is no competitive equilibrium (which can happen when the fitting problem occurs at the margin); a "pseudo-competitive equilibrium price" is found by ignoring the rejected bidders (so it is possible that $b_i - p' * x_i > 0$ for some i that do not trade) and by ignoring the marginal orders. We charge the marginal traders what they bid or offered. If possible we then find a competitive set of prices for the remaining accepted orders, so that no one pays more than they bid or receives less than they ask and revenue (ignoring transaction fees) sums to zero. The problem is we can't always find competitive prices for these assets.

This leaves a subset of bids that are accepted but not marginal. If a competitive price does exist it will not necessarily satisfy Walras' Law over

Figure 1: *No competitive equilibrium, example 1.*

all of the accepted bids (although it will over the non-marginal accepted bids). So instead of computing a single price, two prices are computed one for buyers and one for sellers (again purely in the name of symmetry). So the "pseudo-equilibrium" computed is the "two price" equivalent of the competitive equilibrium price with the additional constraint that all "excluded bids" must pay what they bid. This is usually true for marginal units in a competitive equilibrium, so we interpret that signal here in the same way — if you are charged what you bid then you must be marginal and adjustments in your bid can have significant effects on your final utility.

5.6 Example: non-existence of competitive equilibrium

Consider an inflexible buyer (B1) who is willing to pay \$9 for 3 units and no fewer. An inflexible seller (S1) who is willing to sell 2 units for \$4 and an inflexible seller (S2) who is willing to sell 1 unit for \$6. Welfare is maximized, given the flexibility constraints, if B1 is fully allocated, S1 is fully allocated, and S2 is fully allocated. Welfare is $9 - 4 - 4 =$ \$1; with 3 units traded. There is no other possible allocation that gives positive welfare. However, a per unit competitive price does not exist for this allocation. To see this observe that at any price above \$3 per unit B1 would not be willing to purchase, and at any price below \$4 per unit S2 would not be willing to sell, see Figure 1.

If the traders had been perfectly flexible (only B1 is required to be flexible) then the allocation would have B1 buying 2 units from S1 at a competitive price of \$2.50 (splitting the welfare) and a total surplus of \$2. But since B1 is inflexible, S2 sells a unit at a per unit price above that asked by B1. This "extra marginal" unit is priced so that no surplus is gained from it. All surplus is assigned to those units that would have been allocated if the traders had been fully flexible.

The pricing mechanism, creates a "pseudo-competitive" price pair. In this example, S2 receives \$4 for his one unit, B1 buys one unit at \$3 and 2 units at \$2.75 a unit, S1 receives \$2.25 a unit. S1 receives \$4.50 for a 50 cent surplus, B1 pays \$8.50 ($= 3 + 5.50$) for a 50 cent surplus, and S2 receives \$4 for a unit for 0 surplus. Net revenue is 0 (this example ignores transaction fees).

Figure 2: *No competitive equilibrium, example 2.*

If B1 had been flexible then in the competitive outcome, B1 and S1 would have traded 2 units at a price of \$2.50 per unit, this would have given B1 a \$1 surplus and provides an incentive for B1 to be flexible. While S2 receives a higher per unit price than S1, he runs the risk that in the next round B1 would increase flexibility or S1 (or another seller) would increase their units offered, S1 being the marginal seller would be the first seller dropped from the transaction.

However, even these prices may not exist; as shown in the Let B1 be willing to pay \$9 for 1 unit and B2 be willing to pay \$9 for 3 units. Let S1 be willing to sell 2 units for \$4 and S2 be willing to sell 2 units for \$8.20. All orders are inflexible. In this case the full allocation gives a surplus of \$5.80, see Figure 2.

Since B2 and S2 are marginal S2 receives his ask price for his 2 units and B2 receives his bid for his 2 marginal units. This leaves a deficit of \$2.20 that must be made up by the difference between the price B1 pays for his unit and the price S1 receives for his units. If bids were completely flexible the competitive price would be in the interval between \$2 and \$3, but even if the buyer's and seller's price are at these upper and lower bounds, it would only allow a deficit of \$2 to be covered. So we cannot set prices that would be competitive if all bids were flexible. So that net revenue is zero, buyer and seller prices must be set between \$3.20 and \$9.00, and they only apply to buyer one's and seller one's first unit. The only prices that allow an equal split in surplus between S1 and B1 are \$3.90 for S1 and \$6.10 for B1. In this case B1 receives a ($9-6.10 = \$2.90$) surplus and S1 receives a ($5+2-4 = \$2$) surplus. B2 and S2 receive a surplus of 0.

It should be noted that the above examples have only one asset, with multiple asset packages the pricing complications are multiplied.

5.7 Experiments with the "G" mechanism

To test our mechanism construct a testbed environment (see Plott (1994) for a discussion on designing experimental testbeds), which we call the AUSM and TaK environment and which was described in session 18 and 25. This was the environment that produced the lowest observed efficiencies and misallocations in our tests of the iterative call market. The instructions are

	session 1				session 2				session 3			
round	Eff	Rev	Q_A	Q_B	Eff	Rev	Q_A	Q_B	Eff	Rev	Q_A	Q_B
1	68	146	20	18	79	123	17	19	64	103	15	18
2	70	177	15	19	80	235	16	20	87	202	20	13
3	72	233	18	19	87	300	20	20	87	339	20	20
4	87	397	20	20	95	419	20	20	95	379	20	20
5	87	419	20	12	95	419	20	20	87	440	20	20
6	91	450	17	20					100	490	20	19
7	91	450	15	20								
8	91	450	17	20								

Table 12: *Results of the "G" mechanism, in the AUSM environment (markets A and B), observed efficiency (Eff), revenue (Rev), and quantity sold (Q_A, Q_B).*

supplied in Appendix A.

We conducted 3 experimental sessions (G1, G2 and G3) of the "G" mechanism. It produced allocations that were noticeably more efficient than the iterative sealed-bid call market in the same environments. Final efficiencies were 91, 95, and 100 percent for the AUSM environment and 100 percent for the TaK environment. These efficiencies were realized even though the allocations in the earlier rounds were very low, (*e.g.,* there were no allocations in the first rounds of market C), see Tables 12 and 13.

In addition, no units were over-bought as in the call market and increases in surplus usually lead to increases in efficiency (only once did efficiency decrease). Also, smaller packages of the optimal allocation were easier to allocate. In 19 bidding rounds, the number 2 package 5x4 was allocated 15 times, the number 3 package 3x6 allocated 16 times, but the number 1 12x9 package was allocated only once. In the call market ......

AUSM of Banks *et al.* obtained an average 86 percent efficiency in the AUSM environment. This may be because of the improved incentives of the uniform price property of the "G" mechanism, as opposed to the first price payment in Banks *et al.*, which was a one-sided auction. So compared to the iterative call market and AUSM the "G" mechanism performed quite well.

	session 1			session 2			session 3		
round	Eff	Rev	Q_C	Eff	Rev	Q_C	Eff	Rev	Q_C
1	0	0		0	0		0	0	
2	0	0		0	0		0	0	
3	0	0		0	0		0	0	
4	0	0		100	255		100	281	
5	0	0		100	255		100	281	
6	0	0							
7	100	289							
8	100	289							

Table 13: *Results of the "G" mechanism, TaK environment (market C), observed efficiency (Eff), revenue (Rev), and quantity sold (Q_C).*

6 Results of the ACE market

To judge the success of the ACE market we can only measure its usage and the extent to which its features are being used. Table 14) provides a summary of the RTC market for the years 1994, 1995, and 1996. During that time there were two other methods available to trade RTCs. Trades could be accomplished by bilateral agreements, perhaps arranged by a broker, or trading could be transacted through the Cantor-Fitzgerald (CF-auc) single iteration, sealed-bid brokered auction. Since all trades must be registered at the AQMD we know the total number of trades during a given year, but not how they were traded; we can make an estimate of the CF-auc from their advertisement literature.

The ACE auction appears to have been successful in making trades. In the four ACE auctions 11% to 44% (see Table 14) of the submitted sells where traded, it is difficult to state whether this is good performance, since there is no basis of comparison.

To look at the participants behavior in the ACE market, we will focus on the NOx zone 1 market of February 1996. We can observe that after the first round the number of agents participating (making orders) is relatively steady. But "serious" activity does not take place until the later rounds. The number of RTCs committed in the first round is less than 1 percent of the number of RTCs traded in the last round. The drop in Active RTCs and the number of RTCs offered to sell after the third round is due to the drop in offers to sell RTC credits for years after 2001, perhaps because of the lack of buyers in the first 3 rounds for these RTCs. So while most of the committed

Auction	date	RTCs traded	Sells submitted	Percent transacted	Active traders
CF-auc	July 94	125,000	?	?	?
	Total 94	4,500,000			
CF-auc	Jan 95	615,871	10,500,000	6	28*
ACE	April 95	47,000	285,050	16	17
ACE	July 95	2,410,380	6,472,680	37	22
	Total 95	??			
ACE	Feb 96	1,963,855	17,340,000	11	26
ACE	Apr 96	5,225,000	11,877,000	44	24
ACE	Oct 96	1,487,595			
ACE	July 96	2,410,470	6,012,680	40	
	Total 96	??			

Table 14: *RTC trades made in the ACE market, Cantor-Fitzgerald brokered auction, and total RECLAIM trades registered with the SCAQMD. Note *: Not all traders where active in the market.*

Round	Number of Traders placing orders	Number of orders	RTCs offered (000s) buy	sell	RTCs traded (000s)
1	9	38	623	11,421	13
2	15	63	860	14,001	18
3	13	87	2,604	13,830	70
4	15	62	2,807	5,456	118
5	16	66	8,500	5,511	1934

Table 15: Zone 1 NOx RTC traders, number of orders, RTCs offered to sell and bid to buy, and RTCs committed in a round, February 1996.

trades occurred in the last two rounds, earlier rounds supplied important signals. In this market package bidding was used extensively, there were a few contingent bids, but swapping was rarely used. Inflexible orders where used for up to 23% of the orders. This is important information, in that it reflects directly on computational complexity. The higher percentage of inflexible bids and the larger number of OR sets increases computation time (because of the 0/1 integer constraints).

Almost all the allocated orders were single RTC orders, only 3 allocated sellers used package orders. Flexible bids were important, since 10 out of 29 allocated bids were not fully allocated. There was only a small number of committed trades in the early rounds, but this increased 100 fold in the later rounds. Possibly some way could be found to encourage active participation earlier. Just as has been found in a number of experimental environments, buyers seemed reluctant to place orders in the earlier rounds.

7 Concluding remarks

There did not appear to be any problems with the market, users appeared to be satisfied; but this could will only be conclusive if participation increases in future markets. A substantial amount of work is still required to improve the market mechanism, but it is encouraging that the market appears to work. There are still many questions on how to design mechanisms in complex environment. What stopping rules to use, what update rules, what is the best way to convey market information. How can we improve the pricing rule. We have shown that a market with complex package bidding can be implemented. Can we encourage early bidding, encourage using the public bids.

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