FOUNDATIONS OF COMPUTING AND DECISION SCIENCES
Vol. 38 (2013) No. 4

DOI: 10.2478/fcds-2013-0012 ISSN 0867-6356
e-ISSN 2300-3405

AGENT-BASED EVOLUTIONARY METHOD OF SIMULATION THE CO_2 EMISSION PERMITS MARKET

Jarosław Stańczak*

Abstract. This article describes the problem of simulation of the CO_2 emission permits market. First, it introduces a CO_2 permission market model with transactions and purchase prices, in particular with a separate goal function for each party, transactions with price negotiations between regions and - as a consequence of introducing prices for permits – the possibility of investigating the influence of purchase/sale prices on the market. The behavior of such market model is simulated using a method, which is based on a specialized evolutionary method but introduces independent agents with their own transaction preferences.

Keywords: emission permits market, evolutionary algorithms, agent systems

1. Introduction

Observations of global weather conditions and climate fluctuations convinced many people that global warming could be a real threat for human civilization. Many researchers claim that emission of CO_2 and other greenhouse gases may be the reason of these dangerous changes. Even if this reason is not fully true, limitation of emission harmful gases is also a good reason for introducing reduction mechanisms. Thus, great efforts are being made to reduce these emissions and costs of their implementation. One of proposed methods helping in decreasing the cost of reducing emissions is to implement a system of emission permits for countries and a market of emission trading. It is commonly claimed that this is an efficient strategy for decreasing greenhouse gases emission and probably reducing the global climate warming effect. Parties participating in an emission permits system have limitations imposed on their emissions. If the limitations are too low for some countries, they can choose one of the following solutions: buy permits from other countries, or reduce their emissions by applying new technologies to produce more of their energy needs without the combustion (for instance nuclear power) or using fuels emitting lower amounts of greenhouse gases (for instance gas combustion instead of coal combustion). An accepted

* Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland

solution should depend on their decisions, based on economic condition of the party and derived strategies of emission reduction cost optimization. This approach to emission reduction has been signed by many countries of the world under the Kyoto Protocol. When investigating the influence of the Kyoto Protocol limitations on the world economy, researchers build models of such a market and try to find optimal purchase/sale strategies for their countries. A market model, enabling the forecasting of the quantities and prices of traded emission allowances and the cost of emission reduction for different countries is clearly needed. It is important to build a transaction model and to solve many other problems associated with the credibility of and uncertainty regarding emission level reports, [6], [8], [10] and [13]. The early models of emission permits trading for CO_2 ([7]) do not include real transaction prices. Only the prices at the equilibrium point are calculated via the model (by deriving the cost of emission reduction). Unfortunately, they are not practically applicable, except the equilibrium point. The main aim of optimization in this model is to find the equilibrium point, at which the prices faced by all the countries participating in the market are equal, but not the simulation of the market behavior tending from some starting point to the equilibrium. In this standard model neither negotiation of prices nor additional transaction costs are considered. The participants of this market are assumed to conduct the relevant transactions with the theoretical, optimal prices and thus the optimal solution is given by the equilibrium point.

Newer methods (also this used in this paper) do not assume such an ideal and simplified market. Dynamic market models are applied with some typical elements of a real market, such as the possibility of bilateral or multilateral transactions ([7]), but without negotiation mechanism and considering the influence of negotiated prices. The presented model supplements this possibility and allows tracking the influence of real prices on the resulting solutions (similar assumptions can be found in [3]). It is assumed that the market converges to the equilibrium after a sequence of transactions. The number of transactions between the start of the market and equilibrium is not known in advance. However, each transaction that is profitable for contracting parties (only transactions profitable for participants are accepted during simulations) brings the market toward equilibrium. Thus, convergence under the new model is assured if the considered parameters of the market are proper. Detailed assumptions describing the new market model are given in the next section.

The application of evolutionary algorithms (EAs) in economic simulation models ([5]) has gained considerable attention, mainly due to the fact that economic systems may be quite easily modeled using this kind of tool. An evolutionary and agent-based approach to dynamic market modeling can be found in [3] and [11], where this method is used to simulate the very complicated market of the information sector or gas trading. The paper [12] introduces a similar to presented in this article method of the permit market simulation using agents in JADE environment.

2. A dynamic market model

The Kyoto Protocol imposes severe constraints on the CO_2 emissions of the participating countries but it also proposes mechanisms to exceed them. The participants can buy additional permits from countries that emit less than their limit or can easily decrease their emission. This possibility constitutes some kind of a market for emission permits buying/selling. For a purchasing country, trading is beneficial only when the price of permits is lower than the cost of reducing emissions of CO_2 by the appropriate level. The country that wants to offer permits on the market can also decrease its emission levels by more than it is obliged and sell excess permits. Decreasing its emissions by more than given by the Kyoto target is sometimes beneficial, but selling permits should bring more money than the costs of emission abatement.

A simple Walrasian model of an emissions market is described by equation (1) ([7]). This model assumes that prices are calculated by some market authority on the basis of supply and demand in a market and all transactions are conducted according to this price. The total cost of decreasing emissions in a region (a country or a source) i down to x_i is denoted by $C_i(x_i)$ (the abatement cost function). It is assumed that the cost functions $C_i(x_i)$ are positive, decreasing, continuous and differentiable for each region. The Kyoto limit imposed on region i is denoted $K_{i.}$ The additional level of emissions permitted to participant i based on purchasing permits is expressed by s_i (s_i is negative if i is a net supplier of permits).

$$E = \min_x \sum_{i=1}^{n} C_i(x_i) \tag{1}$$

$$x_i \le K_i + s_i \quad \text{and} \quad \sum_{i=1}^{n} s_i = 0 \tag{2}$$

where E – minimum total cost of decreasing emissions for all countries in the standard model; $C_i(x_i)$ –the costs of decreasing emission in i from an initial value x_{0i} down to x_i; s_i – the additional level of permits acquired by i; K_i – Kyoto target for participant i; n – number of participants; x_i – emission of participant i.

The goal is to minimize the costs of reducing emissions to reach the overall Kyoto target, while fulfilling the needs of participants. However, the optimal value obtained from this model can be far from the real market optimum due to many inaccuracies in the parameter values used and simplification of real phenomena. Typically, many factors influence the prices of goods and the same mechanisms may play a role in the permits market. In the approach described the most important factors are, of course, the estimated costs of emissions reduction, but it is possible to consider different elements. The dynamic model with transactions and negotiated prices, proposed in [14], [15] and [16] is closer to the free market, where countries independently make decisions on buying or selling permits taking into account prices and possible benefits, than the Walrasian model. It is assumed in the dynamic model that a transaction is finalized only when the negotiated price of a permit is lower than the cost of reduction for the buyer and higher than the cost for the seller. Otherwise, the transaction is not profitable to at least one of the participants. It is obvious that each party wants to maximize its profit.

The most important change between the standard, static model, described by (1) and (2) and presented here dynamic model is a different objective function (3), which contains separate equations for each party and shows the influence of permit prices on conducted transactions. In the standard model one function values the market and according to it, total costs of reducing emissions are minimized. The proposed model introduces separate quality functions for all participants. This set of objective functions maximizes the difference between costs with no trading of permits and costs in the case of trading plus expenditures for the permits independently for each participant. For one party the quality function is a sum of costs and benefits gained during all participated transactions. These quality functions take into account the purchase/sale prices of permits, which considerably influence the profitability of transactions and the decision to buy/sell permits, i.e. whether it is better to reduce emissions rather than to buy permits. Formulae (3-9) are constraints ensuring that the market model has realistic properties:

- a participant cannot emit more than its Kyoto obligation plus acquired permits – (4);
- purchased/sold emission permits change the Kyoto obligation for the country – (5);
- additional permits can be bought only from participants in the market, no extra permits are available – (6);
- the number of units traded in one transaction is limited to s_{max} to avoid large perturbations of permit prices – (7);
- the sale and the purchase prices are the same – (8);
- the numbers of units traded in a transaction are negative for sellers and positive for buyers and their absolute values are the same – (9).

$$G_{ij} = \max_{s_{ji},\pi_{ji}} \left(C_i(x_{j-1,i}) - \left(C_i(x_{ji}) - s_{ji} \cdot \pi_{ji} \right) \right) \tag{3}$$

$$x_{Ti} \le K_i + \sum_{j=1}^{T} s_{ji} \tag{4}$$

$$x_{ji} = x_{j-1,i} + s_{ji}, \quad x_{0i} = K_i \tag{5}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{T} s_{ji} = 0 \tag{6}$$

$$s_{\min} \le s_{ji} \le s_{\max}, \quad s_{\min} > 0 \tag{7}$$

$$\pi_{ji} = \begin{cases} 0 & \text{for parties not trading in transaction } j \\ \text{positive value} & \text{for parties trading in transaction } j \end{cases} \tag{8}$$

$$s_{ji} = \begin{cases} 0 & \text{for parties not trading in transaction } j \\ \text{negative value} & \text{for the party selling in transaction } j \\ \text{positive value} & \text{for the party buying in transaction } j \end{cases} \tag{9}$$

$$i = 1, \ldots, n$$
$$j=1,.., T$$

where G_{ij} – the objective function (profit), which each party (i) maximizes making transaction j, the difference between reduction costs without and with trading; T – number of transactions conducted; $C_i(x_{ji})$ – the costs of decreasing emissions by the participant i from the initial value x_{0i} to the value x_{ji} after j transactions; K_i – Kyoto target for the participant i; n – number of participants; x_{ji} – emissions of the participant i after j transactions; s_{ji} – the number of units of emissions acquired by the participant i in the transaction j; s_{min}, s_{max} – the minimum and maximum number of units allowed to be traded in one transaction; π_{ji} – price of permits bought/sold by the participant i in the transaction j.

Using the objective functions (3), it is possible to find solutions, which maximize the difference between the cost without trade (or before current transaction) - $C_i(x_{j-1,i})$ and the cost with trade (after current transaction) - $C_i(x_{ji})$, considering costs of that transaction – $s_{ji}*\pi_{ji}$. In other words the profit from emission trading for particular participants. The goal function is simply an income gained for each party in each transaction. According to objective function (1), the cost of emission reduction, not including the trading of permits, is minimized. However, the purchasing costs may be considerable in comparison to the cost of CO_2 reduction if there were no trade. The simulations of this model bring also another conclusion which leads a different method of setting permit prices to prevent the situation in which the price of a permit can drop to zero. The participants of a market must set a minimal price, below which the price of a permit cannot decrease. According to the model described, the process of negotiations may lead to the situation that at early stages of the market's evolution, zero is selected as the price of a permit in a contract. It is possible that the permit price (defined as a derivative of the cost function in particular point, described by current emission) of the selling country is zero when this country reports initial emissions below the Kyoto level ($K_i>x_{0i}$ – this case occurs for the party EEFSU in described further simulations, see section 4 and Tab. 1). Therefore, its base price (base price is meant as a derivative of the abatement cost function at the current emission point) for negotiations for one unit of emissions should not be the derivative of the abatement cost, but the derivative with the minimal value (13). In practical cases, price negotiations prevent the situation where the price of permits drops to zero, because no country would like to sell them for free. Similar situations may also occur in the standard model, when the needs of the buying countries are less than the surplus of the selling countries and equilibrium of the market will establish emission levels lower than the Kyoto target ($x_i<K_i$) for selling countries. Thus, it seems reasonable that the models described should have some kind of protection against such cases and imposing a minimal price for permits is one of the possible solutions.

The dynamic model introduces transactions among parties. Transactions are performed iteratively until none can be conducted (since there is no benefit to at least one participant without a loss for others). The number of transactions – T in formula (5) - is not known in advance, before the simulations. It depends on local agreements between regions and may be different in simulations with the same market parameters. However, the model is convergent in a finite number of transactions to vicinity (depending on the stop condition) of the market equilibrium with almost equal shadow prices[1] of buyers and sellers. This results from the fact that the cost functions are decreasing and monotonic and only profitable transactions are accepted. Besides, the minimum value imposed on number of units allowed to be traded in one transaction prevents the situation of infinite and asymptotic convergence. Also oscillations are impossible, because they lead to unprofitable transactions. The maximum number of transactions for party i (T_i) is lower than $\widehat{s}_i / s_{\min}$ and bigger than $\widehat{s}_i / s_{\max}$, where $\widehat{s}_i$ is the number of permissions that the party i must purchase to get to the market equilibrium point from its initial state. Thus T as a sum of T_i is also finite. In consequence, transactions decrease the difference between the shadow prices of trading parties and lead to the equilibrium with very close prices. In the simulations concluded the final prices are not exactly equal because transactions are conducted with minimum value of units or packets of permits (7) to be purchased/sold in one transaction. It is useless to make a transaction to transfer very small amounts of permits just to obtain ideal equilibrium. The cost of the transaction may be higher than benefits from such transaction. Transactions on real markets are made to gain some benefits, not to get ideal equilibrium prices.

3. Agent-based evolutionary method

The method

Agent-based evolutionary method can be treated as a specialized, developed version of the evolutionary algorithm. The scheme of its operation is presented in Algorithm 1. In this method each trading party constitutes a separate agent and the population of members in the basic evolutionary algorithm is narrowed to the number of parties participating in the trade. Each member of the population has its own quality function and tries to optimize it, contrary to the standard EA method, where there is one function value for all market participants. This approach allows parties to optimize their actions independently and receive results for their actions, instead only averaging the results of all parties. There is no selection of individuals, because agents are not allowed to die. Instead of it, they select strategies of price bidding and transaction types they want to conduct to obtain better benefits from the market. The strategies are presented in section 3.4. Agents select them on the basis of their experiences. Agents can cancel transaction if the negotiated price is unprofitable or profits are too small. The stop condition can be considered in two meanings. The first is the predetermined number of iterations - the simulation is stopped after it. But more interesting is the fact that earlier transactions are stopped due to lack of profits to be gained. Unfortunately it is difficult to foresee the number of conducted transactions. The equilibrium point obtained in this method is almost the same as in the standard model (1) but the results obtained by parties may be quite different.

[1] The shadow price is the value of the Lagrange multiplier at the optimal solution of the optimization problem.

1. Initialization of agents.
2. Agents choose operators/transactions according to gathered experience.
3. Beneficial operators/transactions are performed, non-beneficial are rejected.
4. New agents' states and selection strategies are recalculated.
5. If a stop condition not satisfied, go to step 2.

Algorithm 1. Agent-based evolutionary market simulation method.

Agent encoding

Each individual in the agent-evolutionary method contains information to be used in market simulation. The information needed to describe all actions of agent/population members is as follows and is encoded as a vector of eight numbers:
- the marginal cost (shadow price);
- the real current price of a permit for sale/purchase;
- the real current value of a permit for sale/purchase;
- the current number of units for sale/purchase;
- the net number of units sold/purchased ;
- the current emissions level;
- the previous emissions level (before the present transaction);
- present (after transaction *j*) and previous (after transaction *j*-1) values of the objective function.

Operators – market transactions

To modify agents-solutions, the following specialized operators were used:
- bilateral sale – two randomly chosen countries conduct price negotiations and if they agree, the solution is modified;
- tender I – a country offers a number of permits for sale, other countries submit offers to buy, the best submitted offer is chosen by the calling party and then the states of the winner and seller are modified; as before, this mechanism has been used in a limited scale;
- tender II – countries offer that want to buy numbers of permits with, seller chooses the best option.

All operators are executed in consecutive iterations during simulations. If agent wants to take part in transaction, it makes offer and joins it. Agents conduct ranking of profits gained using the operators and try to take part in more profitable ones more frequently. The method of computing quality factors is based on reinforcement learning ([4])2. The agent

[2] The described mechanism of operator selection is universal and can be applied in a wide range of agent or evolutionary algorithms, not only those connected with market simulations. The notions "reward", "agent", "strategy" and "policy" are typically used in

selects one of the operators/transactions. When the ith operator is chosen, it can be regarded as an agent's action ai leading to a new state zi, which, in this case, is a new solution. An agent receives a reward (also reinforcement value or payoff) or penalty rt depending on the quality (the value of the fitness function) of the new state (solution). The aim of each agent is to perform the actions (the set of actions performed constitutes a strategy or decision policy, *Π*), which give the highest long term discounted cumulative reward (or total discounted reinforcement over its lifetime) V*. The formula (11) can be derived from (10) and is used for evaluation purposes.

$$V^* = \max_{\Pi} \left(V^{\Pi}\right) \text{ and } V^{\Pi} = E_{\Pi}\left\{\sum_{k=0}^{\infty} \gamma^k r_{t+k+1}\right\} \quad (10)$$

$$V_{ij}(s_{t+1}) = V_{ij}(s_t) + \alpha \cdot \left(r_{i,j,t+1} + \gamma \cdot V^*(s_{t+1}) - V_{ij}(s_t)\right) \quad (11)$$

where Π - represents the strategy of the agent, V^{Π} - represents the discounted cumulative reward obtained using strategy Π, E - represents the expected value, k - represents consecutive time steps, t - represents the current iteration, $V_{ij}(z_t)$ - is a quality factor or the discounted cumulative reward of the i^{th} agent valued after execution the j^{th} operator/transaction at iteration t, V^*- estimated value of the best quality factor (in the experiments the value obtained using the best operator), α is a learning factor, γ is a discount factor (values of α and γ were set to 0.1 and 0.2, respectively), $r_{i,j,t+1}$ - represents the reward obtained when the i^{th} agent takes part in the j^{th} transaction, which is equal to the improvement in the quality of the agent after execution of the operator: $r_{i,j,t+1}=G_{i,j,t+1} - G_{i,j,t}$ (G is the value of the fitness function, as in formula (3)).

Operators described in Section 3.4 mimic market transactions and they require application of intelligent agents. Agents have to use some strategies for bidding prices and for negotiations. In the bilateral sale pairs of contractors are selected randomly from these who want to take part in this transaction. Each of them must bid a starting price to begin negotiations, where they try to reach the price step by step. The negotiations succeed when they accept the same or very close price. If one of them reaches earlier its limit of profitability (shadow price) and the second refuses to accept the actual price, the negotiations fail and no transaction is conducted. Similarly, in the tender each potential contractor must bid a price. If the price is too low, it is very likely that someone gives better price. If it is too high, but of course lower than the limit of profitability, the gain will be small. All participants (for both operators) conduct their bidding ranking in tables of bids. Separate tables are prepared for buying and selling. Market participants store there the gains and numbers of succeeded transactions. The indexes of the tables are the fractions of bidding prices in proportion to the current shadow price, with step 10% (0% - 100%). Bids are selected from the table using the roulette wheel, and the better bids (bids which gave bigger gain) are used proportionally more frequently. The numbers of offered permits are also taken into account during bidding or negotiations and are also stored in two-dimension

the domain of reinforcement learning and have mainly a different meaning to similar notions used in agent systems, economics or in the domain of market games.

tables (2D table of gains), where the second index is a number of traded units (the first is the price index of the first bid, as above).

4. Computer simulation results

The following participants are taken into account: USA, EU, Japan, Canada-Australia-New Zealand (CANZ) and Eastern Europe with the former Soviet Union (EEFSU) ([2], [9] and [13]). The data presented and used are rather approximate. For instance, data for the USA are considered, although this country has not signed the Kyoto protocol yet. Since it would be difficult in practice to start the CO_2 permit market omitting the country with the highest CO_2 emissions level in the world, the USA were usually considered in simulations. The results presented in this section also take this country into account to preserve compatibility with earlier results, but the CO_2 permit market has finally started without the USA. This means that the real prices of permits are lower than those obtained from various models assuming the presence of the USA, because of the significantly lower demand from buying countries. The costs of emissions abatement depend on the value of emission reduction using a quadratic cost function ([2], [9]), presented in equation (13). The marginal prices are derivatives of the cost function, with a small modification – the introduction of the value *min_p* which is the minimal price for permits, preventing the situation in which permits are sold at price 0, which may occur when the costs of emission reduction are 0 for a party with $x_{i0}<K_i$.

$$C_i(x) = \begin{cases} a_i * (x_{i0} - x_i)^2 & \text{for} \quad x_i < x_{i0} \\ 0 \quad \text{for} \quad x_i \geq x_{i0} \end{cases} \tag{12}$$

$$c_i(x) = \begin{cases} \min\left(\left(-2 * a_i * (x_{i0} - x_i)\right), min\_p\right) & \text{for} \quad x_i < x_{i0} \\ min\_p \quad \text{for} \quad x_i \geq x_{i0} \end{cases} \tag{13}$$

where $C_i(x_i)$ - cost function for emissions abatement for country i; a – cost function parameter; x_{i0} – initial emissions; x_i – current emissions, $c_i(x_i)$ – modified marginal price of emissions permit; *min_p* – minimum price of permits.

Country (region)	Initial emissions (x_0) MtC/y	Cost function parameter (a) MUSD/(MtC/y)^2	Kyoto limit (K_i) MtC/y
USA	1820.3	0.2755	1251
EU	1038.0	0.9065	860
Japan	350.0	2.4665	258
CANZ	312.7	1.1080	215
EEFSU	898.6	0.7845	1314

Table 1. The data applied to the calculations.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1561.6	142.5	310.8	44289.0	18433.0	62722.0
EU	959.4	142.5	99.1	14121.8	5602.0	19723.8
Japan	321.1	142.5	63.5	9048.8	2059.0	11107.8
CANZ	248.4	142.5	32.9	4688.2	4583.0	9271.2
EEFSU	807.8	142.5	-506.3	-72147.8	6473.0	-65674.8
Total	3988.3	-	0.0	0.0	37150.0	37150.0

Table 2. Results under the assumption of a perfect permit market.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reductio n MUSD/y
USA	1561.5	142.6	142.2	310.6	18445.3	44185.6	62630.9
EU	959.6	142.2	142.2	99.6	5577.8	6388.3	11966.1
Japan	321.0	143.1	142.8	63.0	2074.3	2896.6	4971.0
CANZ	248.3	142.7	142.4	33.3	4595.5	-8346.8	-3751.3
EEFSU	807.6	142.8	142.8	-506.5	6498.2	-45123.7	- 38625.5
Total	3898.0	-	-	0.0	37191.1	0.0	37191.1

Table 3. Results of market simulation with all transaction types.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1561.6	142.5	142.1	310.6	18436.7	44802.0	63238.7
EU	959.4	142.5	142.4	99.4	5599.1	4252.9	9852.0
Japan	321.0	143.0	142.0	63.0	2074.3	-565.3	1509.1
CANZ	248.3	142.6	142.0	33.3	4591.2	-11137.3	-6546.1
EEFSU	807.6	142.7	142.7	-506.3	6489.7	-37352.3	-30862.5
Total	3897.9	-	-	0.0	37191.1	0.0	37191.1

Table 4. Results of market simulation obtained using bilateral transaction.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1554.7	146.4	133.4	303.7	19442.6	61474.3	80916.9
EU	959.8	141.7	133.6	99.8	5542.8	19943.6	25486.4
Japan	321.8	139.3	136.8	63.8	1969.2	15678.8	17647.9
CANZ	248.8	141.6	134.6	33.8	4524.3	3527.8	8052.1
EEFSU	812.9	134.4	134.2	-501.1	5758.7	-100624.0	-94865.8
Total	3898.0	-	-	0.0	37237.5	0.0	37237.5

Table 5. Results of market simulation obtained using tender I transaction.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1554.3	146.6	144.7	303.3	19495.6	37669.9	57165.5
EU	960.9	139.8	143.3	100.9	5387.4	7146.0	12533.5
Japan	321.3	141.7	143.3	63.3	2037.3	3021.0	5058.2
CANZ	249.9	139.2	144.3	34.9	4374.2	-8157.8	-3783.5
EEFSU	811.6	136.4	144.9	-502.4	5933.8	-39679.2	-33745.3
Total	3898.0	-	-	0.0	37228.3	0.0	37228.3

Table 6. Results of market simulation obtained using tender II transaction.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1561.7	142.5	142.1	310.7	18418.2	45009.6	63427.7
EU	959.6	142.2	142.1	99.6	5577.8	6551.5	12129.2
Japan	321.0	143.1	142.6	63.0	2074.3	2095.8	4170.1
CANZ	248.2	142.9	142.4	33.2	4611.2	-9318.4	-4707.2
EEFSU	807.5	142.9	142.9	-506.5	6509.7	-44338.5	-37828.8
Total	3898.0	-	-	0.0	37191.1	0.0	37191.1

Table 7. Results of market simulation obtained using all transaction types with random strategies of bidding and transaction selection.

Country (region)	Final emissions MtC/y	Shadow price USD/tC	Last transaction price USD/tC	Imported permits Mt/y	Expenditure on permits MUSD/y	Emission reduction cost MUSD/y	Permits+ reduction MUSD/y
USA	1562.2	142.2	142.1	311.2	18352.8	31380.6	49733.4
EU	959.5	142.2	142.2	99.5	5579.2	10783.7	16362.9
Japan	321.0	143.1	142.9	63.0	2074.3	5879.12	7953.5
CANZ	248.3	142.8	142.6	33.3	4599.8	-5006.5	-406.7
EEFSU	807.0	143.8	144.2	-506.0	6586.5	-43037.0	-36450.6
Total	3898.0	-	-	0.0	37192.5	0.0	37192.5

Table 8. Results of market simulation obtained using all transaction types with prepared strategies for USA and EEFSU and random strategies of bidding for remaining parties.

As it can be observed, the results presented in Tables 2-8 are quite different. The transaction type and used strategies have a big influence on transaction prices and the overall costs, even obtained points where transactions are finished, are quite different, especially for tender I and II operators/transactions. The tender I transaction (a seller offers permits and chooses the best contract) is the best for general seller - the EEFSU, where it gains the biggest benefits and all other countries must pay for it. On the other hand, the tender II (a buyer offers that wants to buy some permits and chooses the best contract) is the best transaction type for general buyers like the USA. Both tender transactions stop quite far from the equilibrium point presented in Table 2. It is probably caused by the fact that no negotiations are conducted among contractors and even when the shadow prices are quite different, no profitable transaction can be made.

The bilateral transactions tend to almost ideal equilibrium point (negotiations of prices) and are good for "average" parties (EU, Japan, CANZ), the USA and the EEFSU have gained smaller profits using this kind of transaction. Also averaging abilities of this transaction type can be observed in tables presenting results of all transactions with (Table 3) or without (Table 7) special strategies of bidding and operator/transaction selection. The results obtained in these two cases are similar. It is rather a strange result because it says that prepared and used strategies of operator selection have small influence on the market. It is possible, but results from separate operators show that these strategies have big influence on results (strategies of bidding selection are active in that cases even if selection of transaction can not be used) that opposite abilities of tender I and tender II with averaging properties of bilateral one may mask the influence of strategies selected by parties.

Table 8 shows that if only USA and EEFSU use strategies and other parties behave randomly, they have bigger gains (especially USA), than in random case. Besides, obtained results show interdependencies among parties. If one party chooses a profitable transaction but no one wants to make a deal (no one of remaining participants chooses the same transaction type), its preference to perform such transaction is useless at the moment and no transaction can be done.

The Figure1 shows that the bilateral transaction is preferred by all market participants and consequently is the most frequently made contract, profitable for all market participants. The Figure 2 presents an example of the market simulation. As it can be seen, the prices are rather high at the beginning - emission abatement prices are rather high at the beginning. Then they significantly decrease because abatement costs also decrease and are slightly higher at the end, because the price of the general seller (the EEFSU) increases. The EEFSU have sold cheap permits below the Kyoto target and must decrease its emission, which is rather expensive.

The prices presented on the Figure 1 are several times higher than those recorded in the real world. This is caused mainly by the fact that the USA does not take part in the market, thus real demands are smaller and prices too.

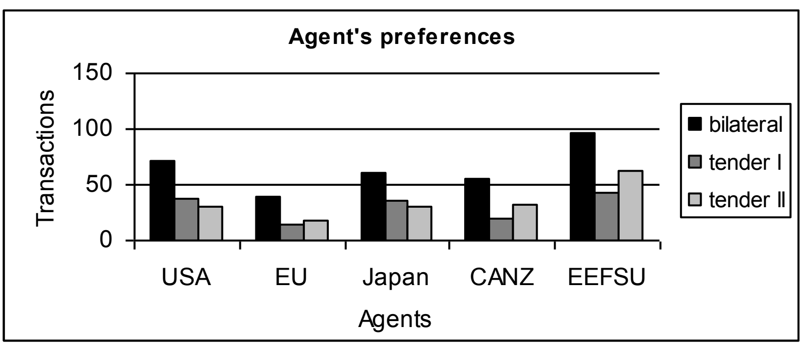

Figure 1. Agent's transaction preferences.

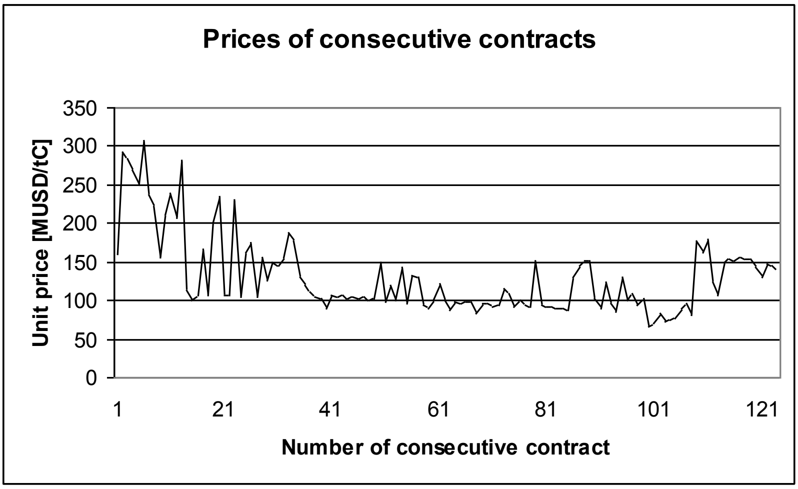

Figure 2. The prices of permits obtained during the trade simulation.

It should be noticed that the final equilibrium price for the market is obtained as a result of small steps – transactions between market participants, not as in the traditional approach – a result of a global calculation. The results obtained are different because the price does not depend only on the shadow price, but also on the difference between the shadow prices of market participants and also on "ability to negotiate". Thus, there are several local equilibrium points for any particular trade between regions and the market simulation stops when no profitable transaction can be made (after *T* transactions).

5. Conclusions

The application of the agent-based evolutionary method to simulation of the permit market gives some additional benefits. The result is not only one set of parameters, but also it is possible to get a set of possible scenarios because the described transactions are conducted in a non-deterministic way. The different scenarios depend mainly on the prices negotiated or/and made contracts. Generally, the final results presented in this paper are similar to these obtained using the standard model. Expenditures on permits constitute the only significant difference, but these costs are important for regions taking part in the CO_2 market, because they constitute the biggest part of financial means engaged. These differences originate from the fact that permit costs are calculated using more realistic assumptions of the market model applied here.

The main advantage of the described method is its ability to take additional factors into consideration, for instance the inclusion of prices for emission permits, negotiations and different models of auctions without the necessity of completely changing the method of solution. Nowadays, EA are often applied in economic simulations, mainly due to the fact that economic systems, with many interactions between their elements, may be quite easily modeled and simulated. The EA-based approach presented seems to be a good tool for analyzing economic phenomena [1], [3], [11], [14]), especially for dynamic market models with elements of uncertainty (negotiated prices). Static models can be simulated using easier and probably faster methods, for instance linear programming.

References

[1] Alkemade F., La Poutre H., Amman H. M. Robust Evolutionary Algorithm Design for Socio-economic Simulation, *Computational Economics 28*, 2006, pp. 355-470.

[2] Bartoszczuk P., Horabik J. Tradable Permit Systems: Considering Uncertainty in Emission Estimates, *Water Air Soil Pollution: Focus (2007) 7*, , Springer Verlag, 2007, pp 573-579.

[3] Bonatti M., Ermoliev Y., Gaivoronski A. Modeling of multi-agent market systems in the presence of uncertainty: The case of information economy, *Robotics and Autonomous Systems*, Vol. 24, Issue 3-4, 1998, pp. 93-113.

[4] Cichosz P. *Systemy uczące się* (*Learning systems*; in Polish), WNT, Warszawa, 2000.

[5] Clemens C., Riechmann T. Evolutionary Dynamics in Public Good Games, *Computational Economics*, 28, 2006, pp. 399-420.

[6] Ermoliev Y., Klaassen G., Nentjes A. Adaptive cost-effective ambient charges under incomplete information, *Journal of Environmental Economics and Management*, 31, 1996, pp. 37-48.

[7] Ermoliev Y., Michalevich M., Nentjes A. Markets for Tradable Emission and Ambient Permits: A dynamic approach, *Environmental and Resource Economics*, 15, 2000, pp. 39-56.

[8] Godal O. Simulating the Carbon Permit Market with Imperfect Observations of Emissions: Approaching Equilibrium through Sequential Bilateral Trade, *Interim Report IR-00-060*, IIASA, Laxenburg, Austria, 2000.

[9] Horabik J. On the costs of reducing GHG emissions and its underlying uncertainties in the context of carbon trading, *Raport Badawczy RB/34/2005*, IBS PAN, 2005.

[10] Klaasen G., Nentjes A., Smith M. Testing the dynamic theory of emissions trading: Experimental evidence for global carbon trading, *Interim Report IR-01-063*, IIASA, Laxenburg, Austria, 2001.

[11] Klaasen G., Matrosov I., Roehrl A., Tarasyev A. A Game-Dynamic Model of Gas Transportation Routes and Its Application to the Turkish Gas Market, *Interim Report IR-03-018*, IIASA, Laxenburg, Austria, 2003.

[12] Mutlu F., Fescioglu-Unver N. Agent Based Simulation of Carbon Emissions Trading Market, *Proceedings of PICMET '11 (Technology Management in the Energy Smart World)*, 2011, pp. 1-10.

[13] Nahorski Z., Horabik J., Jonas M. Compliance and emissions trading under the Kyoto protocol; *Rules for Uncertain Inventories*, Water, Air, & Soil Pollution: Focus, Vol. 7, Numbers 4-5, Springer Verlag, 2007, pp. 539-558.

[14] Stańczak J. Evolutionary algorithm for market simulations, *Evolutionary Computation and Global Optimization 2009*, Prace Naukowe PW, Elektronika, z. 169, Warszawa, 2009, pp. 163-172.

[15] Stańczak J. Application of an evolutionary algorithm to simulation of the CO_2 emission permits market with purchase prices, *Badania operacyjne i decyzje*, 4, 2009, pp. 93-108.
[16] Stańczak J., Bartoszczuk P. CO_2 emission trading model with trading prices, *Climatic Change*, 103 (1-2), 2010, pp. 291-301.

Presented at the XII Conference: Systems and Operational Research – BOS 2012, 17-19 September 2012, Warsaw, Poland