Preferential Partner Selection in Evolutionary Labor Markets: A Study in Agent-Based Computational Economics[⋆]

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Abstract. This paper reports on computational experiments for an agent-based computational economics (ACE) model of a labor market with choice and refusal of contractual partners and endogenously evolving work-site behavior. Three types of labor market structures are examined: two-sided markets comprising workers and employers; partially fluid markets comprising pure workers, pure employers, and agents capable of functioning both as workers and as employers; and endogenous-type markets in which each agent is capable of functioning as both a worker and an employer. Particular attention is focused on experimentally determined correlations between market structure and the formation and evolution of contractual networks, and between contractual network formation and the types of work-site interactions and social welfare outcomes that these contractual networks support.

1 Introduction

Many economists have recently undertaken empirical investigations of the potential costs and benefits of alternative labor market institutions. A primary motivation for these studies has been the difficult restructuring issues faced by transition economies in Eastern Europe as well as the differential labor market experiences of the United States and Europe; see, for example, Nickell [7]. Unfortunately, these studies have been hindered by small sample sizes, and this problem has been compounded by the potential endogeneity of labor market institutions. Poor labor market outcomes may alter the selection of labor market institutions so that institutions and outcomes are jointly determined.

The potential costs and benefits of alternative labor market institutions have also been investigated by means of analytical modelling. Indeed, an interesting theoretical literature stressing job search and matching in labor markets has flourished since the influential work by Diamond [3] on search equilibrium; see, for example, Aghion and Howitt [1]. Yet significant problems are encountered here as well. Tractability issues have generally forced the use of strong

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restrictions on the potential variability of worker and employer behavior. For example, theoretical job search and matching studies commonly postulate an aggregate matching function that proxies the complicated process of employer recruitment, worker search, and mutual evaluation, and attention is typically restricted to steady-state equilibria.

Some of the problems encountered in these empirical and analytical labor market studies may be alleviated by turning to agent-based computational economics (ACE) models. Roughly defined, ACE is the computational study of economies modelled as evolving decentralized systems of autonomous interacting agents. ACE is thus a specialization to economics of the basic artificial life paradigm (Tesfatsion [10]). A key concern of ACE researchers is to understand how global economic regularities arise from the local interactions of autonomous agents channeled through socio-economic institutions rather than through fictitious coordinating mechanisms such as imposed equilibrium conditions.[2]

The ACE model of a labor market developed in this study builds on the Trade Network Game developed by Tesfatsion [9] for studying the formation and evolution of trade networks under alternatively specified market structures. The labor market model is implemented by means of the C++ framework developed by McFadzean and Tesfatsion [6], which in turn is supported by SimBioSys, a general C++ class library for evolutionary simulations developed by McFadzean [5]. As will be demonstrated in the following sections, the model permits the computational study of labor markets at three different levels of analysis: (a) individual work-site interactions between workers and employers; (b) the formation and evolution of contractual networks among workers and employers; and (c) social welfare outcomes as measured by the overall payoffs obtained by workers and employers from repeated work-site interactions.

2 The Basic Model

This section gives a brief overview of the basic modules of the Trade Network Game (TNG) as implemented for the labor market study at hand. A detailed discussion of these modules can be found in [6].

The TNG consists of a collection of traders that evolves over time. As depicted in Table 1, each trader in the initial generation is constructed and assigned a random trade strategy. The traders then enter into a nested pair of cycle loops during which they repeatedly determine trade partners, carry out trades, update their expectations, and evolve their trade behavior over time.

For the labor market application at hand, alternative market structures are imposed through the pre-specification of workers and employers and through the pre-specification of quotas on work offer submissions and acceptances. More precisely, the set of traders is taken to be the union $V = W \cup E$ of a nonempty subset W of *workers* who can submit work offers and a nonempty subset E of

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[2] Additional information about ACE, including surveys, an annotated syllabus of readings, and pointers to software and related Web sites, can be found at the ACE Web site linked to the author's home page.

```
int main () {
  Init();                       // Construct the initial trader generation
                                //    with random trade strategies.
  For (G = 1,...,GMax) {        // Enter the generation cycle loop.
                                // Generation Cycle:
    InitGen();                  //    Configure traders with user-supplied
                                //       parameter values (initial expected
                                //       payoff levels, quotas,...).
    For (I = 1,...,IMax) {      //    Enter the trade cycle loop.
                                //    Trade Cycle:
      MatchTraders();           //       Determine trade partners,
                                //          given expected payoffs,
                                //          and record refusal and
                                //          wallflower payoffs.
      Trade();                  //       Implement trades and
                                //          record trade payoffs.
      UpdateExp();              //       Update expected payoffs
    }                           //          using newly recorded payoffs.
                                //    Environmental Step:
    AssessFitness();            //       Assess trader fitness scores.
    Output();                   //       Output trader information.
                                //    Evolution Step:
    EvolveGen();                //       Evolve a new trader generation.
  }
  Return 0;
}
```

Table 1. Pseudo-Code for the TNG

employers who can receive work offers, where W and E may be disjoint, overlapping, or coincident. A trader is classified as a pure worker, a pure employer, or a worker-employer if he is an element of V/E, V/W, or $W \cap E$, respectively. In each trade cycle, each worker can have no more than wq work offers outstanding to employers at any given time, and each employer can accept no more than eq work offers from workers, where the work offer quota wq and the acceptance quota eq can be any positive integers. Although highly simplified, these parametric specifications permit the study of a variety of labor market structures operating under different ex ante capacity constraints.

If an employer accepts a work offer from a worker in some given trade cycle, the worker and employer are said to be *matched* for that trade cycle. Each such match constitutes a mutually agreed upon contract stating that the worker shall be employed at the work site of the employer until the beginning of the next trade cycle. These contracts are risky in that outcomes are not assured.

Specifically, each matched worker-employer pair engages in a work-site interaction modelled as a two-person prisoner's dilemma game. The worker can either cooperate (exert high work effort) or defect (engage in shirking). Similarly, the employer can either cooperate (provide good working conditions) or defect (provide substandard working conditions). The range of possible payoffs is the same for each match in each trade cycle: namely, L (the sucker payoff) is the lowest possible payoff, received by a cooperator whose contractual partner defects; D is the payoff received by a defector whose contractual partner also defects; C is the payoff received by a cooperator whose contractual partner also cooperates; and H (the temptation payoff) is the highest possible payoff, received by a defector whose contractual partner cooperates. More precisely, the payoffs are assumed to satisfy $L < D < 0 < C < H$, with $(L + H)/2 < C$.

Matches between workers and employers are determined using a modified version of the well-known Gale-Shapley deferred acceptance mechanism; see [8]. Under this modified mechanism, hereafter referred to as the *deferred choice and refusal* (DCR) mechanism, each worker submits up to wq work offers to employers he ranks as most preferable on the basis of expected payoff and who he judges to be tolerable in the sense that their expected payoff is not negative. Similarly, each employer selects up to eq of his received offers that he finds tolerable and most preferable on the basis of expected payoff and he places them on a waiting list; all other offers are refused. Workers redirect refused offers to tolerable preferred employers who have not yet refused them, if any such employers exist. Once employers stop receiving new offers, they accept all work offers currently on their waiting lists. A worker incurs a transactions cost in the form of a negative *refusal payoff* R whenever an employer refuses one of his offers during the matching process; the employer who does the refusing is not penalized. A trader who neither submits nor accepts work offers during the matching process receives a *wallflower payoff 0*.

Traders use a simple learning algorithm to update their expected payoffs on the basis of new payoff information. Each trader v assigns an exogenously given initial expected payoff U^o to each potential contractual partner z with whom he has not yet interacted. Once interactions with z take place, v calculates his updated expected payoff assessment for z by forming the average of U^o plus all payoffs received in past interactions with z.

The work-site behavior of each trader is represented as a finite-memory pure strategy for playing a prisoner's dilemma game with an arbitrary partner an indefinite number of times, hereafter referred to as a *work-site strategy*. At the end of each trade cycle loop, the work-site strategies of pure workers, pure employers, and worker-employers are separately evolved by means of a standardly specified genetic algorithm involving elitism, mutation, and two-point cross-over operations. This evolution is meant to reflect the formation and transmission of new ideas rather than biological reproduction. Specifically, if a work-site strategy successfully results in high fitness for a trader of a particular type, where fitness is measured by average payoff, then other traders of the same type are led to modify their own strategies to more closely resemble the successful strategy.

3 Descriptive Statistics

3.1 Classification of Contractual Network Types by Distance

Let s denote the seed value for the initialization of the TNG random number generator, and let e denote a *potential TNG economy*, i.e., an economy characterized structurally by the TNG source code together with all of the user-specified

TNG parameter values apart from s. The *realized TNG economy* generated from e, given the seed value s, is denoted by (s, e).

Since work-site strategies are represented as finite state machines, the actions undertaken by any trader v in repeated work-site interactions with another trader z must eventually cycle. Consequently, these actions can be summarized in the form of a *work-site history* $H{:}P$, where the *handshake* H is a (possibly null) string of work-site actions that form a non-repeated pattern and the *persistent portion* P is a (possibly null) string of work-site actions that are cyclically repeated. For example, letting c denote cooperation and d denote defection, the work-site history $ddd{:}dc$ indicates that v defected against z in his first three work-site interactions with z and thereafter alternated between defection and cooperation.

Two traders v and z are said to exhibit a *persistent contractual relationhip* during a given trade cycle loop T of a realized TNG economy (s,e) if the following two conditions hold: (a) their work-site histories with each other during the course of T take the form $H_v{:}P_v$ and $H_z{:}P_z$ with nonnull P_v and P_z; and (b) accepted work offers between v and z do not permanently cease during T either by choice (a permanent switch away to strictly preferred contractual partners) or by refusal (one trader becoming intolerable to the other because his expected payoff drops below zero).

A possible pattern of contractual relationships among the traders $V(e)$ in the final generation of a potential TNG economy e is referred to as a *contractual network*, denoted generically by $K(e)$. Each contractual network $K(e)$ is represented in the form of a directed graph in which the nodes of the graph represent the traders $V(e)$, the edges of the graph (directed arrows) represent work offers directed from workers to employers, and the edge weight on any edge denotes the number of accepted work offers (contracts) between the worker and employer connected by the edge.

Let $V^o(e)$ denote a *base contractual pattern* that partially or fully specifies a potential pattern of contractual relationships among the traders $V(e)$ in the potential TNG economy e. For example, $V^o(e)$ could designate that each worker directs offers to at least two employers. Let $K^o(e)$ denote the *base contractual network class* consisting of all contractual networks $K(e)$ whose edges conform to the base contractual pattern $V^o(e)$. Also, let $K(s, e)$ denote the contractual network depicting the actual pattern of contractual relationships among the traders $V(e)$ in the final generation of the realized TNG economy (s, e). The reduced form contractual network $K^p(s, e)$ derived from $K(s, e)$ by setting to zero all edge weights of $K(s, e)$ that correspond to non-persistent contractual relationships is referred to as the *persistent contractual network* for (s, e).

The *distance* $D^o(s, e)$ between the persistent contractual network $K^p(s, e)$ and the base contractual network class $K^o(e)$ for a realized TNG economy (s, e) is then defined to be the number of nodes (traders) in $K^p(s, e)$ whose arrow patterns (persistent contractual relationships) fail to conform to the base contractual pattern $V^o(e)$. This distance measure provides a rough way to classify the different types of persistent contractual networks observed to arise for a given value of e as the seed value s is varied.

3.2 Classification of Work-Site Behaviors

A trader v in a realized TNG economy (s, e) is referred to as an *unprovoked defector (UD)* if he engages in at least one defection against another trader who has not previously defected against him. The vector giving the separate UD percentages for pure workers, pure employers, and worker-employers in the final generation of (s, e) is referred to as the *UD profile* for (s, e). The UD profile measures the extent to which the different types of traders behave agressively in work-site interactions with contractual partners who are either strangers or who so far have been consistently cooperative.

Moreover, v is referred to as a *persistent wallflower (PW)* if v constitutes an isolated node of the persistent contractual network $K^p(s, e)$. Alternatively, v is referred to as a *persistent defector (PD)* if v establishes at least one persistent contractual relationship for which the persistent portion P of his work-site history $H{:}P$ includes a defection d. If, instead, v establishes at least one persistent contractual relationship and his work-site history for each of his persistent contractual relationships has the general form $H{:}c$, he is referred to as a *persistent cooperator (PC)*.

The vectors giving the separate PW, PD, and PC percentages for pure workers, pure employers, and worker-employers in the final generation of (s, e) are referred to as the *PW profile*, the *PD profile*, and the *PC profile* for (s, e), respectively. The PW profile measures the extent to which the different types of traders fail to establish any persistent contractual relationships, whereas the PD and PC profiles measure the extent to which the different types of traders establish persistent contractual relationships characterized by predacious or fully cooperative behavior, respectively. By construction, a trader must either be a PW, a PD, or a PC. Thus, only the PW and PC profiles are reported in the experiments discussed below.

The vector giving the separate mean average fitness scores for pure workers, pure employers, and worker-employers in the final generation of a realized TNG economy (s, e) is referred to as the *FIT profile* for (s, e). The FIT profile constitutes a measure of social welfare.

4 Brief Summary of Experimental Findings

The experiments conducted to date for the labor market application at hand focus on three simple labor market structures: two-sided markets comprising 12 pure workers and 12 pure employers; partially fluid markets comprising 8 pure workers, 8 pure employers, and 8 worker-employers; and endogenous-type markets comprising 24 worker-employers. Within each market structure, four different configurations for the worker offer quota wq and employer acceptance quota eq are examined: high excess capacity ($eq >> wq$); zero excess capacity ($eq = wq = 1$); tight capacity ($eq = 1$ and $wq = 2$); and extremely tight capacity

```
// PARAMETER VALUES FIXED ACROSS EXPERIMENTS
    GMax = 50                  // Total number of generations.
    IMax = 150                 // Number of trade cycles in each trade cycle loop.
    MutationRate = .005        // GA bit toggle probability.
    FsmStates = 16             // Number of internal FSM states.
    FsmMemory = 1              // FSM memory (in bits) allocated to past move recall.
    RefusalPayoff = -0.5       // Payoff R received by a refused trader.
    WallflowerPayoff = +0.0    // Payoff received by an inactive trader.
    Sucker = -1.6              // Lowest possible trade payoff, L.
    BothDefect = -0.6          // Mutual defection trade payoff, D.
    BothCoop = +1.4            // Mutual cooperation trade payoff, C.
    Temptation = +3.4          // Highest possible trade payoff, H.
    InitExpPayoff = +1.4       // Initial expected payoff level, U^o.
// PARAMETER VALUES VARIED ACROSS EXPERIMENTS
    TraderCount = 24           // Total number of workers and employers.
    PureWorkers = 12           // Number of pure workers.
    PureEmployers = 12         // Number of pure employers.
    WorkerEmployers = 0        // Number of worker-employers.
    Elite = 8                  // Number of elite for each nonzero trader type.
    WorkerQuota = 1            // Worker offer quota wq.
    EmployerQuota = 12         // Employer acceptance quota eq.
```

Table 2. Parameter Values for a Two-Sided Market with High Excess Capacity

$(eq << wq)$. The genetic algorithm elite value is automatically adjusted in each experiment to maintain the elite proportion at approximately two thirds for each nonzero trader type.

The values for all remaining parameters are maintained at fixed values throughout all experiments. Table 2 lists these fixed parameter values along with the specific trader type values, quota values, and elite value for a two-sided market experiment with high excess capacity. The parameter values in Table 2, together with the TNG source code, constitute a potential TNG economy e in the sense defined in Section 3.

For each tested e, twenty TNG economies (s, e) were experimentally generated using twenty arbitrarily selected seed values s for the TNG pseudo-random number generator. The persistent trade network $K^p(s, e)$ for each run s was determined and graphically depicted, and the mean and standard deviation for the UD, PW, PC, and FIT profiles were determined and recorded.

A base contractual pattern $V^o(e)$ was then specified for each tested e. Although the choice of this base pattern is simply a normalization determining a 0 point for the distance measure D^o, and hence intrinsically arbitrary, the degree of specificity of this base pattern governs the dispersion of the resulting distance values and the extent to which these distance values display useful correlations with work-site behaviors as measured by the UD, PW, PC, and FIT profiles. In practice, then, the choice of the base contractual pattern was fine-tuned so that the resulting distance values provided a meaningful informative classification of network types. Given $V^o(e)$, the distance $D^o(s, e)$ of $K^p(s, e)$ from $K^o(e)$

was recorded for each run s, and a histogram for the distance values $D^o(s,e)$ was constructed giving the percentage of runs s corresponding to each possible distance value.

One interesting finding observed for many of the tested economies e is the existence of multiple distinct types of persistent contractual networks $K^p(s,e)$, each supporting a distinct pattern of work-site behaviors. More precisely, the distance values for the persistent contractual networks tend to cluster around a small number of isolated distance values, and the mean distance of each distance cluster tends to be strongly correlated with the mean UD, PD, PW, PC, and FIT profiles calculated for the cluster. For such economies, then, there does not appear to be any central-tendency network in the sense defined in [2] but rather a number of different local basins of attraction. One possible explanation for these distinct distance clusters is that they correspond to multiple Nash equilibria for the underlying evolutionary match-and-play game in which the traders are participating. On the other hand, the distinct distance clusters could be artifacts of the relatively small sample size of 20 that was used in these experiments in order to keep the graphical determination and analysis of network formations manageable. More testing is needed here.

A second interesting finding is that the optimality criteria conventionally used to evaluate the performance of matching mechanisms in static market contexts turn out to be highly incomplete indicators of performance from an evolutionary vantage point. The static viewpoint hides the strong role played by market structure and ex ante capacity constraints in determining the types of persistent matching networks that evolve, the types of persistent interaction behaviors that these networks support, and the transactions costs and inactivity costs to agents that the achievement of these persistent networks and behaviors entails. In addition, the static viewpoint takes preference rankings over potential partners as given whereas these rankings are continually updated on the basis of past interactions in evolutionary settings. Indeed, matching networks and interaction behaviors evolve conjointly. This suggests the need for more comprehensive optimality criteria that take both facets into account.

More concretely, in all of the labor market experiments reported here, the DCR mechanism described in Section 2 is used to match workers and employers. The matching outcomes generated via the DCR mechanism have been shown (Tesfatsion [9]) to have the usual optimality properties associated with Gale-Shapley type matching mechanisms: namely, pairwise stability; and Pareto optimality from the vantage point of workers, the agents who actively make offers. Nevertheless, the actual evolutionary outcomes observed in these labor market experiments include autarkic economies in which all traders are persistent wallflowers, parasitic economies in which employers persistently defect against cooperate workers or workers persistently defect against cooperative employers, and fully harmonious economies in which all traders are persistent cooperators. Moreover, due to transactions costs (negative R payoffs) and inactivity costs (0 wallflower payoffs), social welfare can still be low even if all active traders are persistent cooperators. These evolutionary outcomes are systematically related to market structure and to ex ante capacity constraints as captured by the worker offer quota wq and the employer acceptance quota eq.

For example, consider an endogenous-type labor market economy e comprising 24 worker-employers with a worker offer quota $wq = 1$ and an employer acceptance quota $eq = 24$. These quota values indicate that e has a high excess capacity in the sense that the total number of work offers the employers can accept in each trade cycle far exceeds the maximum number of work offers that workers can make. The base contractual pattern $V^o(e)$ for this economy e is as follows: Each worker-employer directs work offers to other worker-employers without latching.[3] For this e, 90% of the runs (s, e) were observed to lie in the distance cluster 0–3. This means that, for each (s, e), at most 3 of the 24 worker-employers in the final trader generation deviated from the base contractual pattern. For this distance cluster, the mean UD profile was 3%, the mean PW profile was 1%, the mean PC profile was 96%, and the mean FIT profile was 1.37.

Next consider the case of a two-sided labor market economy e comprising 12 pure workers and 12 pure employers with a worker offer quota $wq = 1$ and an employer acceptance quota $eq = 12$, implying once again a high excess capacity. The base contractual pattern $V^o(e)$ for this economy e is as follows: Each worker is latched to at least one employer, and no employer is a wallflower. For this e, 75% of the runs (s, e) were observed to lie in the distance cluster 3–9 and 25% were observed to lie in the distance cluster 23–24.

In the first distance cluster, the mean UD profile for workers and employers was $(97\%, 16\%)$, the mean PW profile was $(2\%, 40\%)$, the mean PC profile was $(3\%, 39\%)$, and the mean FIT profile was $(1.76, 0.37)$. The very low mean FIT value of 0.37 for employers is due to two factors: high accumulation of wallflower payoffs due to high excess capacity; and aggressive and persistently predacious behavior by workers. Indeed, the persistent contractual networks for this distance cluster reveal that workers are latching on to a selected subset of employers and driving down their fitness scores to small positive values, causing the remaining employers to become PWs with fitness scores close to 0. This ensures that the parasitized subset of employers do relatively well in the evolution step, due to the separate evolution of pure workers and pure employers, and so reproduce into the next generation. This in turn ensures a continual source of hosts for the workers to prey upon.

In contrast, in the second distance cluster the mean UD profile for workers and employers was $(2\%, 5\%)$, the mean PW profile was $(2\%, 5\%)$, the mean PC profile was $(98\%, 95\%)$, and the mean FIT profile was $(1.39, 1.03)$. The mean FIT value of 1.03 achieved by employers is substantially below the mutual cooperation payoff level of 1.40 despite the high percentage of PC behavior exhibited by both workers and employers. This low mean FIT value results from the high accumulation of wallflower payoffs by employers due to high excess capacity, a structural cause that is independent of how cooperatively the employers behave

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[3] A worker v is said to be *latched* to an employer z if he works for z continuously (in each successive trade cycle) rather than intermittently (randomly or recurrently).

in their work-site interactions.

Finally, consider the case of a partially-fluid labor market economy e comprising 8 pure workers, 8 pure employers, and 8 worker-employers with a worker offer quota $wq = 1$ and an employer acceptance quota $eq = 16$, again implying a high excess capacity. The base contractual pattern $V^o(e)$ for this economy e is as follows: Each worker directs work offers to employers without latching, and no pure employer is a wallflower. For this e, 30% of the runs (s, e) were observed to lie in distance cluster 0–2, 35% were observed to lie in distance cluster 6–9, and 35% were observed to lie in distance cluster 16–21. In the first distance cluster, although all traders exhibit a high degree of PC behavior, pure employers have a low mean FIT value of 1.02 (relative to mean FIT values of 1.39 and 1.36 for pure workers and worker-employers) due primarily to large accumulations of wallflower payoffs. In the remaining two distance clusters, latching behavior increases substantially as does worker UD and PD behavior and the frequency of PWs among pure workers and pure employers, which results in the generally lower mean FIT profiles of $(1.16, 0.73, 1.25)$ and $(1.15, 0.57, 1.44)$.

In the reverse case of tight capacity, the risk to employers of high wallflower payoffs recedes and is replaced by the risk to workers of high refusal payoff accumulation. Moreover, it is now the employers who are encouraged by their structural setting to engage in UD and PD behavior whereas the risk of refusal encourages relatively high PC behavior among workers. In these settings there is a strong tendency for worker-employers to behave as pure employers.

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