

Elliott, Matthew L.; Nava, Francesco

## Article

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# Decentralized bargaining in matching markets: Efficient stationary equilibria and the core

MATTHEW ELLIOTT

Department of Economics, Cambridge University

FRANCESCO NAVA

Department of Economics, London School of Economics

This paper studies market clearing in matching markets. The model is non-cooperative, fully decentralized, and in Markov strategies. Workers and firms bargain with each other to determine who will be matched with whom and at what terms of trade. Once a worker–firm pair reaches agreement, they exit the market. Alternative possible matches affect agents' bargaining positions. We ask under which conditions such markets clear efficiently and find that inefficiencies—mismatch and delay—feature frequently. Mismatch occurs whenever an agent's bargaining position is at risk of deteriorating. Delay occurs whenever agents expect their bargaining position to improve. Delay can be extensive and structured with vertically differentiated markets endogenously clearing from the top down.

**KEYWORDS.** Bargaining, matching markets, mismatch, delay, search.

**JEL CLASSIFICATION.** C78, L14.

## 1. INTRODUCTION

We study thin matching markets, particularly labor markets, featuring decentralized negotiations that involve heterogeneous agents from both sides of the market. We capture one dimension of heterogeneity through constraints that restrict who can match with whom. Firms might be able to employ only workers they have interviewed, some positions might only be filled through referrals, and some people may simply be unqualified for some positions. On top of this, we allow for variability in how well suited different workers are to fill different vacancies. We take these matching constraints and heterogeneities as given, and ask when decentralized negotiations can clear markets efficiently.

We assume players exit the market once they reach an agreement. Exit shapes the set of alternative matches available to players remaining in the market. We contend that in many decentralized labor markets, agreements are reached sequentially, and the market context in which the remaining workers and firms bargain evolves accordingly.

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Matthew Elliott: [matthew.l.elliott@gmail.com](mailto:matthew.l.elliott@gmail.com)

Francesco Nava: [f.nava@lse.ac.uk](mailto:f.nava@lse.ac.uk)

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For instance, when negotiating with a firm, a worker might use the possibility of taking a position with another firm to achieve a higher wage. But this bargaining stance may be undermined if that position is filled by a different worker. When the changing market context affects the terms that are agreed upon in equilibrium, we find that markets fail to clear efficiently. People delay when they expect the market to evolve in their favor, and match inefficiently when they expect the market to evolve against their interests.

In our model there are multiple buyers, multiple sellers, matching is one-to-one, and each buyer–seller pair generates some pair-specific surplus if matched. Time is infinite, and in each period a single agent is selected at random to make a proposal. The proposer chooses an unmatched player and offers a split of the surplus that the pair would generate if matched. If the offer is accepted, the pair exits the market. If it is rejected, the pair remains in the market. While the nonstationarities created by matched pairs exiting the market complicate matters, the endogenous evolution of the market is central to our results. We find it is this that creates scope for bargaining frictions, and we investigate the role of market evolution in driving inefficiencies, due to both mismatch (inefficient matching) and delay.

We study the Markov perfect equilibria (MPE) in which strategies depend only on the set of players who remain in the market. Restricting attention to such stationary equilibria is common in the bargaining literature,<sup>1</sup> can be motivated on the grounds of complexity,<sup>2</sup> and has received some experimental support.<sup>3</sup>

Our primary focus is on the existence of an efficient MPE (that is, an equilibrium in which buyers and sellers are matched to maximize total surplus) when players are patient (or, equivalently, interactions are frequent). We consider equilibria that are efficient for sufficiently patient players as well as limiting equilibria that become efficient only as the discount factor converges to 1. Interpreting the probability that a player is selected to make an offer as the bargaining power of that player, suppose the surplus generated by an efficiently matched pair is split in proportion to the partners' relative bargaining powers. We refer to these payoffs as agents' *Rubinstein payoffs*, as they would obtain in the limit if all efficient pairs bargained bilaterally.<sup>4</sup> Our first main result establishes that an efficient MPE exists for sufficiently patient players if and only if Rubinstein payoffs are in the core of the market (that is, if no pair of players can deviate and benefit by matching to each other when all players receive their Rubinstein payoffs). Moreover,

<sup>1</sup>See, for example, Rubinstein and Wolinsky (1985, 1990), Gale (1987), Polanski and Winter (2010), and Abreu and Manea (2012b).

<sup>2</sup>Maskin and Tirole (2001) argue for considering MPEs on the basis of complexity. Furthermore, the conclusions of Bhaskar et al. (2013), which are reached in a more general setting and can be applied to our model, imply that only MPEs are purifiable. Finally, Sabourian (2004) provides additional motivation specific to bargaining in markets.

<sup>3</sup>Agranov and Elliott (2017) investigate bargaining in a laboratory experiment in an environment closely related to the one we study. The MPEs organize the data well and substantially better than standard alternative theories, in particular, efficient perfect equilibria. They find empirical support for several predictions we make in this paper.

<sup>4</sup>We refer to these payoffs as Rubinstein payoffs as they are the unique limiting equilibrium outcome in bilateral bargaining settings with random proposers. This is a standard generalization of the bilateral bargaining setting with alternating offers analyzed in Rubinstein (1982).

if this condition holds, all players receive their Rubinstein payoffs in the limit as they become arbitrarily patient. If it is a mutual best response for players to ignore the market context and bargain bilaterally with each other when discount factors are sufficiently high, there exists an MPE in which players do so. As a result, players match efficiently. If not, there is no efficient MPE when players are sufficiently patient. Thus, whenever the market context matters and players' bargaining positions evolve as others exit the market, an efficient MPE does not exist.

To gain some intuition for why there is no efficient MPE when Rubinstein payoffs are outside the core, note that if all players were to bargain just bilaterally with their core matches, they would receive their Rubinstein payoffs, and there would then be at least one player  $i$  who would prefer to deviate and reach agreement with some other player  $j$ . If so, to preserve efficiency, this alternative match would have to serve as a binding outside option, bounding  $i$ 's payoff while not being exercised. However, if  $i$  and  $j$  never agreed, then  $i$ 's efficient partner would benefit by waiting for  $j$  to exit the market and by agreeing with  $i$  only when his bargaining position decays. Thus, in such instances, there is no equilibrium in which all players agree with their efficient partners with certainty.

This intuition also identifies a limitation of the aforementioned efficiency result. If  $j$  never exits before  $i$  in equilibrium, then  $i$ 's efficient partner cannot weaken  $i$ 's bargaining position by delaying. So when there is no danger of binding alternative matching opportunities being lost, we might expect there to be an MPE that is inefficient away from the limit, but that exhibits vanishingly small inefficiencies in the limit as players become arbitrarily patient. Indeed, in a two-player setting, [Sutton \(1986\)](#) establishes that as agents become perfectly patient, outside options can bound payoffs from below while being exercised with a probability converging to zero. Investigating this possibility, we look for MPEs that exhibit vanishing inefficiencies in the limit. We begin by studying MPEs that exhibit no delay or mismatch in the limit. In such equilibria, agents may provide binding alternative matching opportunities and never exit the market because in equilibrium they are unmatched. In this case, a modified version of our main result continues to hold in the limit, and MPEs exhibit no delay or mismatch in the limit only if suitably modified Rubinstein payoffs belong to the core. Permitting delay in the limit, there is another way in which binding alternative matching opportunities might affect payoffs without resulting in mismatch in the limit. This requires players to endogenously exit in sequence. In particular, all players except one efficient pair may choose to delay with probability 1 in the limit while waiting for this pair to reach agreement and exit the market. If so, the agreeing pair of players would have alternative matching opportunities that are never lost before their exit. Consequently, their bargaining positions would not evolve, and alternative matches can bound the payoffs of this pair of players while being exercised with a vanishingly small probability in the limit. It might be reasonable to postulate that no such equilibrium would ever exist, as it requires delay in the limit from pairs of players who expect to be matched with probability 1 in the limit. Perhaps surprisingly, endogenous delay of this form, resulting in sequential exit from the market, can occur in equilibrium. With four players and equal bargaining powers, we find necessary and sufficient conditions for such an MPE to exist. The market must be highly

vertically differentiated and clear from the top. This is consistent with anecdotal evidence from high-skill labor markets. In sports and in the movie industry, markets are sometimes reported to be held up until a star is matched.

Delay is possible in our model despite information being perfect because the order of play is random. As time progresses and matched pairs exit the market, the strength of players' bargaining positions evolves stochastically. Equilibrium delay stems from favorable beliefs about the market evolution (for instance, beliefs about tempting alternative matches for their bargaining partners exiting the market). In limiting equilibria with sequential exit, such favorable beliefs are driven by vanishingly small probabilities of an inefficient match occurring, which increase the expected payoffs of all delaying players.

### *Related literature*

We study decentralized bargaining in thin markets. The prototypical market we intend to speak to is a labor market for highly skilled individuals. Such markets are inherently thin, and characterized by heterogeneities and by decentralized negotiations. Our approach is closest to the literature analyzing non-cooperative bargaining in thin markets. This literature takes the coalitional bargaining approach, but restricts the coalitions that can generate surplus and reach agreement to pairs of players. As there are large literatures considering coalitional approaches to non-cooperative bargaining and bargaining in large markets, we do not attempt a complete review of these. Instead, we just highlight some of the most closely related work.

Because of the additional generality, coalitional bargaining models are typically a better fit for political negotiations and committee decision making. The closest papers to ours in this literature, [Moldovanu and Winter \(1995\)](#) and [Okada \(2011\)](#), also link cooperative and non-cooperative approaches. Moldovanu and Winter consider a bargaining model without discounting and with deterministic proposer orders. They find conditions on the proposer order for a core outcome to be reached in a stationary equilibrium.<sup>5</sup> The indeterminacy of equilibrium bargaining outcomes caused by the lack of discounting is critical for their analysis. Our conclusions rule out this indeterminacy by studying the limit of a model in which delay costs vanish, but can nevertheless relate players' bargaining power (or, equivalently, proposal probabilities) to the existence of an efficient MPE. Like us, Okada finds conditions under which no efficient MPE exists and he relates these conditions to the core. However, in the assignment economies we consider, the conditions he identifies are generically violated when there are two or more players on each side of the market, implying that an efficient equilibrium never exists.<sup>6</sup> In contrast, an efficient MPE exists for a positive measure subset of the parameter space in our decentralized bargaining model. Moreover, even when such conditions fail, we show that there can be equilibria with vanishing inefficiencies as delay costs become small.

<sup>5</sup>Their main conclusion establishes that a core outcome is reached when there is a stationary equilibrium that holds for any proposer order. In our model, except in trivial cases, an efficient equilibrium never exists for all proposer probabilities.

<sup>6</sup>See Appendix C of the Supplemental Material for a more detailed comparison.

A vast literature has considered decentralized bargaining in large markets, meaning either that the number of players is infinite or that agreeing players are replaced by exact replicas.<sup>7</sup> Seminal work includes Rubinstein and Wolinsky (1985), Gale (1987), and Binmore and Herrero (1988). The literature has focused on deriving conditions for equilibrium outcomes to approximate competitive equilibria (or, equivalently, core outcomes) when the frictions get small. Lauermann (2013) provides a tight characterization of when these two outcomes can be expected to coincide. Most papers in this literature study steady state outcomes,<sup>8</sup> but Moreno and Wooders (2002) is an exception. As in some equilibria of our model, they find delay can occur in the limit, but unlike our model, equilibrium outcomes in their setting are always competitive as players become infinitely patient.

The most closely related work to ours models non-cooperative bargaining without replacement in thin markets. This literature includes Rubinstein and Wolinsky (1990), Corominas-Bosch (2004), Gale and Sabourian (2006), Polanski (2007), Polanski and Winter (2010), Abreu and Manea (2012a, 2012b), and Polanski and Vega-Redondo (2013). These papers embed different degrees of coordination into their bargaining protocols. Corominas-Bosch (2004) investigates the existence of competitive equilibria in markets with homogeneous surpluses (a link in the bipartite network indicates that the two players would generate a unit of surplus if matched) and alternating non-exclusive offers. This setup differs from the one considered here, and requires a high degree of coordination both at the offer stage (as players on one side propose simultaneously to everyone on the other side of the market) and at the acceptance stage (since more than one assignment may be possible). Polanski (2007) also considers a setting with homogeneous surpluses and strong coordination (as a maximum matching is used to select which players bargain bilaterally each period), and links subgame perfect equilibrium outcomes to the Dulmage–Mendelsohn decomposition of the bipartite network.

The closest papers to ours are Gale and Sabourian (2006) and Abreu and Manea (2012a, 2012b). The former differs from us insofar as all players are simultaneously matched into pairs before an agent in each pair is selected to be the proposer with equal probability. Gale and Sabourian include heterogeneous surpluses, but assume that different sellers have identical objects to sell, so that a given buyer generates the same surplus with all sellers. They provide an example in which all MPE payoffs are non-competitive and, therefore, the market outcome is inefficient.

Abreu and Manea (2012a, 2012b) consider environments with homogeneous surpluses in which players cannot necessarily be partitioned into buyers and sellers (implying that a core match might not exist or be unique). One of the extensions of Abreu and Manea (2012a) analyzes a protocol close to the one we consider, but does not restrict attention to Markovian equilibria. Their conclusions prove the existence of nonstationary equilibria that converge to efficiency as the time elapsed between offers vanishes. Abreu and Manea (2012b), like us, focuses on limiting MPEs, but in the context of a

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<sup>7</sup>See Manea (2017) for how the replica assumption relates to steady state outcomes in large markets.

<sup>8</sup>Some examples, with a particular focus on network bargaining, include Atakan (2008), Manea (2011), and Polanski and Lazarova (2015).

bargaining protocol in which players are randomly paired to bargain.<sup>9</sup> As in Gale and Sabourian (2006), an important contribution of their paper is to provide examples in which all MPEs are inefficient. While both Gale and Sabourian (2006) and Abreu and Manea (2012b) identify interesting and important features of market inefficiencies, neither paper provides general conditions to determine whether or not an efficient limiting MPE exists. Yet, such conditions are important so as to assess the extent of bargaining frictions in markets. To pursue this goal, we select a protocol that favors the existence of efficient equilibria and we introduce a slightly stronger notion of efficiency (which we explain in Section 5).

In protocols that select links to determine the proposer, when an inefficient link is selected, players must either disagree or match inefficiently. Allowing players to choose to whom they make an offer prevents delay and mismatch from being necessary features of equilibrium play. Furthermore, it simplifies the characterization of efficient MPEs. In our conclusions, we make this point explicitly by discussing an example contained in Abreu and Manea (2012b). Given the possibility of inefficiency, we select a bargaining protocol that is predisposed to admit an efficient MPE. To clarify the role of bargaining frictions, we further restrict attention to environments in which the surplus maximizing match exists and is unique. This alleviates coordination problems that might arise,<sup>10</sup> and is the generic case whenever the market can be partitioned into two sides. Our results clarify that disagreement is possible even between players who are matched in the unique efficient match, and that the multiplicity of equilibria is driven by the underlying coordination game and not by the multiplicity of core matches. As is customary in the literature, we allow bargaining frictions, represented by the time elapsed between offers, to get small. Despite making these modeling choices, we find inefficiencies to be a common feature in these markets and we find conditions for them to occur.

### Outline

The next two sections introduce the economy (Section 2) and the directed-search bargaining protocol analyzed (Section 3). Section 4 defines solution concepts and presents the baseline characterization. Section 5 introduces our efficiency criteria and relates them to welfare. Several examples preview the main conclusions in Section 6. All the main contributions on stationary equilibrium welfare are given in Section 7. The relationship to the search literature and the alternative bargaining protocols are discussed in Section 8. All the proofs of propositions are provided in the Appendix, whereas the proofs of remarks and several additional robustness checks can be found in the Supplemental Appendixes, available in a supplementary file on the journal website, <http://econtheory.org/supp/2416/supplement.pdf>.

## 2. THE ASSIGNMENT ECONOMY

An *assignment economy* consists of a set of players  $N = \{1, \dots, n\}$  and an  $n$  by  $n$  matrix  $S$  characterizing the surplus that can be generated by any two players in the economy. The

<sup>9</sup>Each period, a link is selected according to some probability distribution; then a player on that link is selected with equal probability to propose.

<sup>10</sup>See Appendix B in the Supplemental Material for a more detailed comparison on this point.

$ij$  entry of  $S$ ,  $s_{ij} \geq 0$ , denotes the surplus generated when players  $i$  and  $j$  are matched. The surplus matrix  $S$  can be interpreted as a network. The network is assumed to be undirected (so that  $s_{ij} = s_{ji}$  for any  $i, j \in N$ ) and bipartite (so that, for some partition  $(P_1, P_2)$  of the set of players  $N$ ,  $s_{ij} = 0$  whenever  $i, j \in P_k$  for  $k \in \{1, 2\}$ ). The two assumptions imply that the surplus generated in a match is independent of the identity of the player who initiates the match, and that surplus can be generated only by players of different types. By assumption, workers generate surplus only with firms, men generate surplus only with women, and buyers generate surplus only with sellers.

A *match* is a map  $\mu : N \rightarrow N$  such that  $\mu(\mu(i)) = i$  for any  $i \in N$ . If  $\mu(i) = i$ , we say that player  $i$  is unmatched. If  $\mu(i) = j$ , then  $i$  and  $j$  generate surplus  $s_{ij}$ . Let  $M(N)$  denote the set of possible matches for a given set of players  $N$ . An *efficient match*  $\eta$  for an assignment economy  $S$  is a match that maximizes surplus:

$$\sum_{i \in N} s_{i\eta(i)} = \max_{\mu \in M(N)} \left\{ \sum_{i \in N} s_{i\mu(i)} \right\}.$$

The *core* of the market consists of the set of match and payoff vector pairs  $(\mu, u)$  that satisfy

$$(C1) \quad u_i + u_{\mu(i)} = s_{i\mu(i)} \text{ for any } i \in N$$

$$(C2) \quad u_i + u_j \geq s_{ij} \text{ for any } i, j \in N.$$

Shapley and Shubik (1971) establish that any core match is an efficient match, and that a unique efficient match exists when no two positive links have the same value.<sup>11</sup> As the condition for uniqueness is generic, our analysis restricts attention to economies with a unique efficient match. Thus, throughout the analysis we refer to the unique efficient match  $\eta$  as the *core match*.

Although condition (C2) only rules out the existence of profitable pairwise deviations, Shapley and Shubik (1971) establish that this suffices to rule out the existence of profitable coalitional deviations. The lowest and the highest payoffs that player  $i$  can receive in a core outcome are denoted by  $\underline{u}_i$  and  $\bar{u}_i$ .

### 3. MATCHING AND BARGAINING

The analysis considers a non-cooperative, infinite-horizon bargaining protocol in which players choose whom to bargain with. All players discount the future by a common factor  $\delta \in (0, 1)$ . At the beginning of the game, all players are active, but they can become inactive as the game unfolds. In every period, a single player  $i \in N$  is selected at random to be the proposer, with probability  $p_i > 0$ . If proposer  $i$  is active, he can make an offer to at most one other active player. We adopt as a convention that a player failing to make an offer chooses to offer to himself. An offer from player  $i$  to a player  $j \neq i$  consists of a surplus split  $x_{ji} \in [0, s_{ij}]$ , where  $x_{ji}$  denotes the amount of surplus generated by the new match,  $s_{ij}$ , that he intends to leave to  $j$ . The player receiving the offer then has a binary

<sup>11</sup>Formally, the efficient match is unique if  $s_{ij} > 0$  implies  $s_{kl} \neq s_{ij}$  for all  $kl \neq ij$ .



choice, to accept (1) or reject (0) the offer. If  $j$  rejects the offer, both players remain active, and the game moves to the next stage. Otherwise, players  $i$  and  $j$  become inactive, and their final payoffs are determined by the discounted value of the shares that they have agreed upon. In particular, the value at the beginning of the game to players  $i$  and  $j$  of reaching an agreement  $x_{ji}$  at stage  $t$  is

$$u_j = \delta^{t-1} x_{ji} \quad \text{and} \quad u_i = \delta^{t-1} (s_{ij} - x_{ji}).$$

In the next stage the proposer is selected according to the same probability distribution.<sup>12</sup> If an inactive player is selected, the game moves to the subsequent period. The game ends when the surplus generated by any pair of active players is zero. The structure of the game is common knowledge among players. Information is perfect. Thus, all players observe any offer previously made and the corresponding acceptance decision.

### *Histories and strategies*

Denote the set of histories at date  $t$  observed by any player after the new proposer has been selected by  $H^t = N \times [N^2 \times \mathbb{R}_+ \times \{0, 1\}]^{t-1}$ . Such histories consist of the identity of the current proposer, the identities of past proposers, to whom they offered, the offer they made, and whether the offer was accepted or rejected. Denote the set of histories of length  $t$  observed after an offer has been made by  $R^t = N \times \mathbb{R}_+ \times H^t$ . Let  $R = \bigcup_t R^t$  and  $H = \bigcup_t H^t$ . Finally, let  $H_i$  denote the subset of histories in  $H$  in which player  $i$  is the proposer, and let  $R_i$  denote the subset of histories in  $R$  in which player  $i$  is the responder.

We say that player  $i \in N$  is *active* at history  $h \in H$  if player  $i$  has never accepted an offer and has never made an offer that was accepted. For any history  $h \in H$ , let  $A(h) \subseteq N$  denote the set of active players after history  $h$ . Throughout,  $\Delta(\cdot)$  denotes the simplex of a finite set. The strategy of an active player  $i \in A(h)$  when making an offer consists of a pair of functions,  $\rho_i$  and  $\chi_i$ , such that

$$\rho_i(h) \in \Delta(A(h)) \quad \text{and} \quad \chi_i(h) \in \mathbb{R}_+^{|A(h)|} \quad \text{for } h \in H_i.$$

The first map  $\rho_i(h)$  describes the probability distribution over players who may receive an offer from  $i$  at any given history, while the second map  $\chi_i(h)$  identifies the amount of surplus that  $i$  would offer to each potential partner. The strategy of an active player  $i \in A(h)$  when receiving an offer instead consists of a single function,  $\alpha_i$ , such that

$$\alpha_i(h) \in [0, 1] \quad \text{for } h \in R_i.$$

The map  $\alpha_i(h)$  describes the probability that an offer is accepted. Strategy profiles are denoted by omitting the dependence on players,  $(\rho, \chi, \alpha) = \{\rho_i, \chi_i, \alpha_i\}_{i \in N}$ .

<sup>12</sup>Results are unaffected by updating proposal probabilities conditional on being active. However, we opted to keep the expected time to propose of each player stationary across periods.

## 4. MPE EXISTENCE AND CHARACTERIZATION

The analysis restricts attention to stationary Markov perfect equilibria in which strategies depend only on the set of active players in the game.

**DEFINITION 1.** A subgame perfect equilibrium  $(\rho, \chi, \alpha)$  is a Markov perfect equilibrium (MPE) if strategies coincide whenever active player sets coincide. That is, for any two histories  $h, h' \in H$  such that  $A(h) = A(h')$ ,

- (i)  $\rho(h) = \rho(h')$  and  $\chi(h) = \chi(h')$
- (ii)  $\alpha(i, x|h) = \alpha(i, x|h')$  for any offer  $(i, x) \in N \times \mathbb{R}_+$ .

Strategies are stationary as the calendar date is not part of the Markov state. Since we consider only stationary MPE, we often omit the word stationary and make the dependence on the active player set explicit (thereby omitting the dependence on histories). The notation  $(\rho^\delta, \chi^\delta, \alpha^\delta)$  is occasionally used to clarify that equilibrium strategies may also depend on the discount factor  $\delta$ , but we omit this dependence when it is redundant.

Some of the results consider MPE behavior in the limit as the discount factor converges to 1. To simplify the discussion, we introduce a notion of limiting equilibrium.

**DEFINITION 2.** A limiting Markov perfect equilibrium (LMPE)  $(\bar{\rho}, \bar{\chi}, \bar{\alpha})$  is the limit of a selection  $\{\rho^\delta, \chi^\delta, \alpha^\delta\}_{\delta=0}^1$  from the MPE correspondence as  $\delta$  converges to 1.

Throughout the text, the expression *equilibrium* refers to an MPE and the expression *limiting equilibrium* refers to an LMPE. To simplify notation, we invoke the following two conventions for all  $i, j \in A$ :

$$A_{-i} = A \setminus \{i\} \quad \text{and} \quad A_{-ij} = A \setminus \{i, j\}.$$

For any MPE  $(\rho, \chi, \alpha)$  and any set of players  $A \subseteq N$ , let  $\pi_{ij}(A)$  denote the *agreement probability* between players  $i \in A$  and  $j \in A_{-i}$  when  $i$  is selected to make an offer,

$$\pi_{ij}(A) = \underbrace{\rho_i(j|A)}_{\text{Pr}(i \text{ offers to } j)} \cdot \underbrace{\alpha_j(i, \chi_i(j|A)|A)}_{\text{Pr}(j \text{ accepts})},$$

and let  $\pi_{ii}(A)$  denote the probability that  $i$  does not reach agreement when selected to make an offer,

$$\pi_{ii}(A) = 1 - \sum_{j \in A_{-i}} \pi_{ij}(A).$$

Also, let  $V_i(A)$  denote the expected payoff—or, equivalently, *value*—of an active player  $i$  at the beginning of a subgame in which the set of active players is  $A$ , and let  $v_i(A)$  denote the MPE value of an active player  $i$  when he is chosen to be the proposer.

We begin by proving equilibrium existence and by providing a preliminary characterization of equilibrium bargaining values. For convenience, let  $p_A = \sum_{j \in A} p_j$ . The characterization allows for mixed strategy equilibria. Fix an active player set  $A$  and

consider any Markovian strategy profile  $(\rho, \chi, \alpha)$  and its associated values and agreement probabilities  $(\pi, V) \in [\Delta(\mathcal{A}) \times \mathbb{R}]^{|\mathcal{A}|}$ , where we omit the dependence on  $\mathcal{A}$  for clarity. As in numerous bargaining models, subgame perfection dictates that a proposer never offers to another player more than that player's present discounted value of staying in the game. As players can choose with whom to bargain, proposers necessarily offer to those players who leave them with the highest surplus,  $\arg \max_{j \in \mathcal{A}-i} \{s_{ij} - \delta V_j\}$ , whenever such surplus exceeds the value  $\delta V_i$  of remaining unmatched. Formally, we define the value of proposing at active player set  $\mathcal{A}$  for a player  $i \in \mathcal{A}$  by

$$v_i = \max \left\{ \delta V_i, \max_{j \in \mathcal{A}-i} \{s_{ij} - \delta V_j\} \right\}.$$

It follows that for any active player set  $\mathcal{A} \subseteq N$ , MPE values  $V(\mathcal{A})$  for any player  $i \in \mathcal{A}$  must be a fixed point of the system of value equations

$$V_i = \underbrace{p_i v_i}_{i \text{ proposes}} + \sum_{j \in \mathcal{A}-i} p_j \left[ \underbrace{(\pi_{ji} + \pi_{jj}) \delta V_i}_{j \text{ agrees with } i \text{ or delays}} + \underbrace{\sum_{k \in \mathcal{A}-ij} \pi_{jk} \delta V_i(\mathcal{A}_{-jk})}_{j \text{ agrees with } k \neq i, j} \right] + \underbrace{(1 - p_{\mathcal{A}}) \delta V_i}_{\text{no player proposes}}$$

for some profile of agreement probabilities  $\pi(\mathcal{A})$  that satisfy

$$\pi_{ij} = \begin{cases} 0 & \text{if } v_i > s_{ij} - \delta V_j \text{ and } j \neq i, \\ 0 & \text{if } v_i > \delta V_i \text{ and } j = i. \end{cases} \tag{1}$$

**PROPOSITION 1.** *An MPE exists. Moreover,  $\{\pi(\mathcal{A}), V(\mathcal{A})\}_{\mathcal{A} \subseteq N}$  is a profile of MPE values and agreement probabilities if and only if it solves system (1) at any active player set  $\mathcal{A} \subseteq N$ .*

Existence is proved by applying Kakutani's fixed point theorem. The result extends Proposition 1 and Lemma 1 in [Abreu and Manea \(2012b\)](#) to environments in which players are allowed to choose to whom to offer and in which the surplus generated in a match depends on the identity of the players. While MPEs are not unique, MPE values are uniquely determined by MPE agreement probabilities.

The result implies that no player  $i \in \mathcal{A}$  can delay with an active player set  $\mathcal{A}$  in equilibrium if there exists a player  $j \in \mathcal{A}$  such that  $\delta V_i + \delta V_j < s_{ij}$ . Thus, in any MPE displaying on-path delay, it must be that  $\delta V_i + \delta V_j \geq s_{ij}$  at some on-path subgame. Moreover, as  $V_i$  and  $V_j$  are a discounted weighted average of the possible future agreements  $i$  and  $j$  can reach on path, if  $i$  and  $j$  delay, they must collectively expect higher payoffs from delaying and letting the market evolve than from reaching agreement now.

### 5. EFFICIENCY, WELFARE, AND DELAY

Next we introduce the two efficiency criteria and the notion of delay that is analyzed in the following sections. Let  $E$  denote the set of unmatched players in the core of the original assignment economy,  $E = \{i \in N \mid \eta(i) = i\}$ , and let  $C(N)$  denote the set of possible

active player sets that may arise as core matches are removed from the game,

$$C(N) = \left\{ A \mid A = \bigcup_{i \in M} \{i, \eta(i)\} \cup E \text{ for some } M \subseteq N \right\}.$$

We are interested in active player sets in  $C(N)$ , as only such subgames can arise with positive probability in equilibria in which players eventually match efficiently. The properties of the core imply that the core partner of every player must coincide at all active player sets  $A \in C(N)$ .

Consider a social planner who is able to impose terms of trade and agreement probabilities, but is otherwise constrained by the environment of the game. For a high enough discount factor, this constrained social planner implements only efficient matches and does so at the first available opportunity. An MPE with these features is said to be *strongly efficient*. It requires that every player who is matched in the core of the assignment economy agrees on a division of surplus with his core partner at the very first opportunity. One way in which surplus can be lost is through delay. However, when delay costs are small (that is, when  $\delta$  is close to 1), little surplus is dissipated by deferring agreements. We therefore also consider a weaker efficiency criterion that requires only that nobody ever matches with players other than their core partner. We refer to these MPEs as *weakly efficient*. Our results then establish that all players must eventually agree on a division of surplus with their core partners in any such MPE.<sup>13</sup>

DEFINITION 3. Consider an MPE  $(\rho, \chi, \alpha)$ .

- If for all  $A \in C(N)$ ,  $\pi_{i\eta(i)}(A) = 1$  for all  $i \in A$ , the MPE is strongly efficient.
- If for all  $A \in C(N)$ ,  $\pi_{i\eta(i)}(A) + \pi_{ii}(A) = 1$  for all  $i \in A$ , the MPE is weakly efficient.

Neither efficiency criterion is satisfied when an inefficient match occurs with positive probability. As we assume  $\delta < 1$ , this may rule out instances in which the agreement probabilities on inefficient matches become negligible as  $\delta \rightarrow 1$ . To address these, we apply the two efficiency criteria to the limiting equilibria. For convenience, given a profile MPE  $(\rho^\delta, \chi^\delta, \alpha^\delta)$  for all  $\delta < 1$ , define the limiting agreement probabilities as  $\bar{\pi}_{ij}(A) = \lim_{\delta \rightarrow 1} \pi_{ij}^\delta(A)$  for all  $i, j \in A$  and the limiting values as  $\bar{V}_i(A) = \lim_{\delta \rightarrow 1} V_i^\delta(A)$  for all  $i \in A$  (when these limits exist).

DEFINITION 4. Consider an LMPE  $(\bar{\rho}, \bar{\chi}, \bar{\alpha})$ .

- If for all  $A \in C(N)$ ,  $\bar{\pi}_{i\eta(i)}(A) = 1$  for all  $i \in A$ , the LMPE is strongly efficient.
- If for all  $A \in C(N)$ ,  $\bar{\pi}_{i\eta(i)}(A) + \bar{\pi}_{ii}(A) = 1$  for all  $i \in A$ , the LMPE is weakly efficient.

<sup>13</sup>In terms of utilitarian welfare, for all  $\delta$  sufficiently high, strongly efficient MPEs maximize the ex ante sum of expected payoffs, whereas weakly efficient MPEs do not unless they are also strongly efficient. Even in strongly efficient MPEs, however, the sum of values is necessarily below the total surplus, as it takes time for the core match to form. Moreover, in a strongly efficient MPE, all active player sets in  $C(N)$  occur with positive probability. But this is not the case for weakly efficient MPEs, as the market may clear sequentially.

While we establish that both strongly and weakly efficient LMPEs generate the same surplus in the limit, it is instructive to separate them for the purpose of classifying limiting efficient equilibrium play. The strong and weak efficiency dichotomy parses efficiency loss through inefficient matching versus inefficient delay. When applying our efficiency criteria to LMPEs, it is worthwhile noting that active player sets outside  $C(N)$  may now occur with positive probability for all  $\delta < 1$ .

As is customary, we refer to the sum of ex ante values,  $\sum_{i \in N} V_i(N)$  as *utilitarian welfare*. The next proposition establishes that utilitarian welfare converges to total surplus,  $\sum_{i \in N} s_{i\eta(i)}$  as  $\delta \rightarrow 1$  in any weakly efficient LMPE. This motivates our efficiency criterion by showing that no welfare can be lost from delay in any such equilibrium.

**PROPOSITION 2.** *Any weakly efficient LMPE maximizes surplus:*

$$\sum_{i \in N} \bar{V}_i(N) = \sum_{i \in N} s_{i\eta(i)}.$$

The result is intuitive and relies on delay costs vanishing at a sufficiently fast rate as  $\delta \rightarrow 1$ . Its proof also establishes why, in any MPE, all players cannot simultaneously delay with positive probability at some active player set. Since weakly efficient LMPEs maximize utilitarian welfare, [Proposition 2](#) implies that these equilibria are always *asymptotically efficient* as defined in [Abreu and Manea \(2012a, 2012b\)](#). In principle though, asymptotically efficient LMPEs may exist in which players match inefficiently at active player sets that belong to  $C(N)$ , but that do not materialize on the equilibrium path.<sup>14</sup> Weakly efficient LMPEs refine asymptotically efficient LMPEs by requiring the equilibrium to be efficient in the limit at any active player set in  $C(N)$ , and not just at those active player sets that are reached with positive probability on path.<sup>15</sup> In doing so, they rule out asymptotically efficient equilibria that are sustained by the threat of inefficient matching at some core subgame, instead requiring a consistent selection of efficient equilibria throughout all subgames that can be reached following efficient matching. Relative to earlier studies, the stronger welfare criterion allows a novel approach that entails first disciplining limiting agreement probabilities in all core subgames and then exploiting the recursive structure of stationary equilibria to derive stronger implications on efficient equilibrium payoffs and on their existence.

Our notion of equilibrium delay requires the existence of a player with a positive value who chooses to forgo the option to make an acceptable offer with positive probability.

<sup>14</sup>If the short side of the market has at most two players,  $\min_i |P_i| = 2$ , then all LMPEs must be weakly efficient in any core subgame  $A \neq N$ . Thus, all asymptotically efficient equilibria must be weakly efficient LMPEs. Moreover, any asymptotically efficient equilibrium, in which all players in  $A \setminus E$  agree with positive probability in every subgame  $A \in C(N)$ , must be a weakly efficient LMPE.

<sup>15</sup>Formally, asymptotically efficient MPEs require the conditions defining weakly efficient LMPEs to hold only for active player sets  $A \in C(N)$  that materialize with positive probability on the equilibrium path, rather than requiring the same conditions but for all  $A \in C(N)$ .

DEFINITION 5. An MPE  $(\rho, \chi, \alpha)$  displays delay if, for some  $A \subseteq N$  and some player  $i \in A$ ,

$$V_i(A) > 0 \quad \text{and} \quad \pi_{ii}(A) > 0.$$

The definition applies only to players with a positive value, as it is immediate that players with zero continuation value might well prefer to disagree. In Section 6, we present two examples in which a player with a positive continuation value chooses to delay on the equilibrium path.

## 6. EXAMPLES

Before proceeding to the main analysis, we consider a few examples to illustrate the model, the solution concepts, and the efficiency definitions, and to preview some of the main conclusions. The first example establishes that equilibrium mismatch can occur. The second shows how mismatch inefficiencies can occur for  $\delta < 1$ , but disappear in the limit, implying that there is a strongly efficient limiting equilibrium. The third example features on-path equilibrium delay, and the fourth example shows a weakly efficient limiting equilibrium in which players delay and endogenously exit the market in a fixed sequence. These examples can be skipped.

EXAMPLE 1. Consider an assignment economy populated by four players who propose with equal probabilities. Surpluses in the market are as depicted in panel I of Figure 1.

The unique efficient assignment matches player  $a$  to  $b$  and player  $c$  to  $d$  whenever  $y < 200$ , while it matches player  $a$  to  $d$  only when  $y > 200$ . Multiple core assignments exist at  $y = 200$ . Proposition 1 can be used to derive MPE payoffs and strategies in this game for any discount factor. To make the discussion more transparent, suppose that the discount factor is close to unity. When  $y \leq 100$ , players make offers only to their core partners. This is equivalent to the scenario where each player bargains bilaterally with his efficient partner, and all players achieve an LMPE payoff of 50. In this case, no player is ever tempted to offer to anyone beside his core match. These equilibrium offer strategies for active players  $A = \{a, b, c, d\}$  are shown in panel II of Figure 1.

For values of  $y \in (100, 200)$ , bilateral bargaining cannot be a solution. Indeed, if everyone offered only to their efficient match, players  $a$  and  $d$  would both have a profitable deviation to offer to each other. When  $y \in (100, 1000/7)$ , players  $a$  and  $d$  randomize in equilibrium between offering to their respective core matches and bargaining with each other (panel III of Figure 1). By offering to each other with positive probability,  $a$  and  $d$  reduce the continuation values of their efficient partners. In equilibrium they do this until they are indifferent between offering to each other and to their efficient partners. As  $y$  increases, this requires the strong players,  $a$  and  $d$ , to offer to each other with higher probability, and at  $y = 1000/7$ , they reach the corner solution in which indifference requires them to offer to each other with probability 1. As  $y$  grows further such that  $y \in [1000/7, 200)$ , players  $a$  and  $d$  continue to offer only to each other, and still accept offers made by their respective core matches (panel IV of Figure 1). Mismatch now

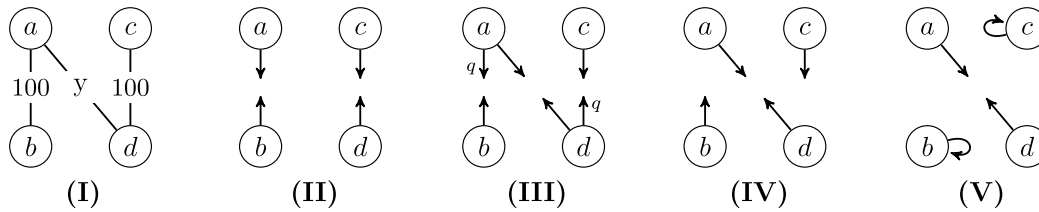


FIGURE 1. Panel I displays the assignment economy. MPE agreement probabilities  $\pi_{ij}(N)$  are shown in panel II for  $y \in [0, 100]$ , in panel III for  $y \in (100, 1000/7]$ , in panel IV for  $y \in (1000/7, 200]$ , and in panel V for  $y \in (200, \infty)$ . An arrow between two players represents a positive agreement probability, while a self-arrow represents a positive disagreement probability.

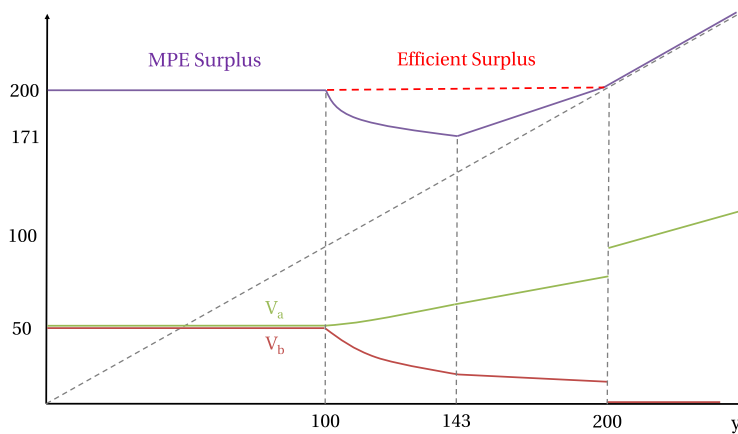


FIGURE 2. Depiction of the limiting payoffs, the limiting MPE surplus, and the limiting efficient surplus as a function of  $s_{ad} = y$  for Example 1. The payoff of players  $a$  and  $d$  is denoted by  $V_a$ , whereas  $V_b$  denotes the payoff of  $b$  and  $c$ .

occurs with probability 1/2. Despite this inefficiency, the unique equilibrium is in pure strategies.<sup>16</sup>

The final case is that where  $y > 200$  and in which the efficient assignment matches player  $a$  to  $d$ . If so, players  $a$  and  $d$  continue offering to each other with probability 1. However,  $b$  and  $c$  stop making offers to players  $a$  and  $d$ , as any acceptable offer would have to exceed the entire surplus in the relevant relationship (panel V of Figure 1). This change affects limiting payoffs discontinuously. When  $y < 200$ , player  $b$  always makes an acceptable offer to  $a$ , leaving  $c$  to bargain bilaterally with  $d$  with probability 1/4. Thus,  $c$  gets a limiting payoff of 50 with probability 1/4. For  $y > 200$ , however,  $b$  stops making acceptable offers to  $a$ , and  $c$  receives a payoff of 0 with certainty. Note that this

<sup>16</sup>For  $y \in (100, 1000/7)$ , in the limit as  $\delta \rightarrow 1$ , players  $a$  and  $d$  make offers to their respective core partners with probability  $q = (2\sqrt{2y^2 - 600y + 50,000} - y)/(200 - y) \in (0, 1)$ . The unique LMPE payoff of players  $a$  and  $d$  amounts to  $V_a = (y + 50 + 50q)/(3 + q)$ , while that of players  $b$  and  $c$  equals  $V_b = V_a - y + 100$ . For  $y \in [1000/7, 200]$ , the LMPE payoff of  $a$  and  $d$  further increases to  $V_a = (y + 50)/3$ , whereas that of  $b$  and  $c$  decreases to  $V_b = (400 - y)/12$ .



FIGURE 3. Panel I displays the assignment economy, while panel II displays MPE agreement. The limiting equilibrium shown is strongly efficient as  $\lim_{\delta \rightarrow 1} q^\delta = 0$ .

discontinuity occurs precisely at the value of  $y$  for which the core match is not unique (Figure 2). ◇

EXAMPLE 2. The next example shows that alternative matches that cannot be lost can act like outside options and bound payoffs while being exercised with probability 0 as players become arbitrarily patient.

Consider the three-player market depicted in panel I of Figure 3. The unique core match of the market matches players  $e$  and  $f$ , leaving  $c$  unmatched. Assume again that players propose with equal probability and that discount factors are sufficiently close to 1. If so, players  $e$  and  $f$  offer to each other with probability 1 in the unique MPE, whereas player  $c$  offers to player  $f$  with probability  $q^\delta \in (0, 1)$ , where  $\lim_{\delta \rightarrow 1} q^\delta = 0$ . Although  $q^\delta \rightarrow 0$  in the limit, the mere presence of player  $c$  significantly affects bargaining outcomes. Players  $e$  and  $f$  would share the 10 units of surplus evenly were they to bargain in solitude. However, because  $c$  never exits the market, he acts like an outside option for  $f$ . Indeed, player  $f$  extracts the same limiting surplus that he would get were he to bargain in solitude with player  $e$  while having access to an outside option with value 8. The limiting payoffs converge to 8 for player  $f$ , to 2 for player  $e$ , and to 0 for player  $c$ . Even though player  $c$  does not make an acceptable offer in the limit, the equilibrium does not display delay by our definition, because the payoff of player  $c$  equals exactly 0 for all  $\delta$  sufficiently close to 1. While the equilibrium described is not strongly or weakly efficient for  $\delta < 1$  due to the positive probability of a mismatch, that probability converges to zero in the limit, and so the limiting equilibrium is strongly efficient.<sup>17</sup> ◇

EXAMPLE 3. In Example 1, we saw that mismatch can arise when players feared losing valuable alternative matches. The next example shows that on-path delay can occur when players expect the market to evolve in their favor.

Consider the six-player assignment economy depicted in panel I of Figure 4, in which agents are selected to propose with equal probability. We show that an equilibrium exists in which  $f$  delays making offers with probability 1 when selected to propose if all other players are still active in the market. Panel II of Figure 4 shows the equilibrium offer strategies in this MPE. To solve this game, we use backward induction. Under

<sup>17</sup>For  $\delta$  close to 1, in the unique MPE of this example, we have that  $V_c(N) = 0$ ,  $V_e(N) = (26\delta - 24)/\delta$ ,  $V_f(N) = 8/\delta$ , and  $q = (27\delta^2 - 63\delta + 36)/(13\delta^2 - 12)$ .



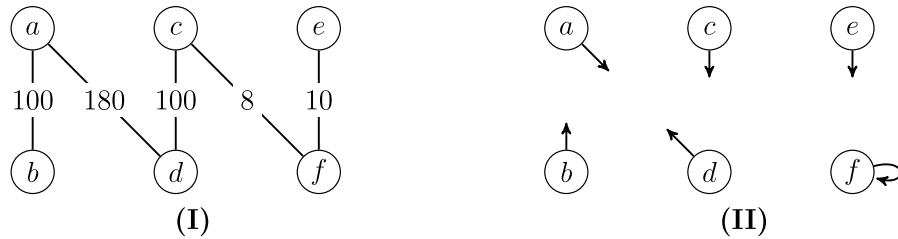


FIGURE 4. Panel I displays the assignment economy, while panel II displays MPE agreement. Player  $f$  delays with probability 1.

the proposed equilibrium, if the protocol selects agent  $e$  as the first proposer, agent  $e$  makes an offer to agent  $f$  that is accepted. If so, the remaining subgame coincides precisely with the game discussed in Example 1, so we know the MPE payoffs for all the remaining players in the subgame. If agent  $c$  is selected as the first proposer and agrees with  $d$ , then in the following subgame, agents  $e$  and  $f$  bargain bilaterally, as do agents  $a$  and  $b$ . If agents  $a$  or  $d$  are selected as the first proposers instead, then agent  $b$  must remain unmatched, while agents  $c$ ,  $e$ , and  $f$  are left in precisely the subgame we considered in Example 2. Finally, if agent  $b$  is the first proposer, he agrees with  $a$ , and players  $c$ ,  $d$ ,  $e$ , and  $f$  are left in a subgame. While we have not solved this subgame yet, in the unique MPE, all players offer to their efficient partner as in Example 1. Limit payoffs for  $c$ ,  $d$ ,  $e$ , and  $f$  are then given by 50, 50, 5, and 5. With these subgames in mind, it is easy to write down the value equations for the six agents and solve them. For instance, the value equation for agent  $c$  simply amounts to

$$V_c(N) = p \left[ \underbrace{2\delta V_c(\mathcal{E}_2)}_{a \text{ or } d \text{ propose}} + \underbrace{\delta V_c(c, d)}_{b \text{ proposes}} + \underbrace{(100 - \delta V_d(N))}_{c \text{ proposes}} + \underbrace{\delta V_c(\mathcal{E}_1)}_{e \text{ proposes}} + \underbrace{\delta V_c(N)}_{f \text{ delays}} \right],$$

where  $V_c(\mathcal{E}_i)$  denotes the value of player  $c$  in Examples  $i \in \{1, 2\}$ . Solving the value functions establishes that no player has a profitable deviation from the proposed strategies, and that player  $f$  must delay for all sufficiently high values of  $\delta$ . Taking limits as  $\delta \rightarrow 1$ , the payoffs of the six players converge to  $V(N) = (55/3, 230/3, 230/3, 55/3, 13/2, 7/2)$ . Agents  $a$  through  $d$  achieve the same limiting values as in Example 1. The additional option available to  $c$  (of matching with  $f$ ) does not improve  $c$ 's terms of trade, as it is never binding. Nevertheless, the option of matching with  $c$  incentivizes  $f$  to delay. There is a positive probability that  $a$  and  $d$  reach agreement first, and in this case,  $f$ 's bargaining position with  $e$  improves. While such threats are factored into the limiting payoff of  $e$ , and  $f$  ends up indifferent between delaying and making an offer to  $e$  when selected to propose first,  $f$  must delay with certainty to extract the maximum possible equilibrium value out of his potential future outside option.<sup>18</sup>  $\diamond$

<sup>18</sup>Delay in this example is driven only by the endogenous evolution of bargaining positions. Players can choose whom to bargain with (which implies that no player has to delay to be matched to his equilibrium partner), and the efficient match is unique (which shuts down possible coordination problems among players). In Appendix B of the Supplemental Material, we show that when multiple efficient matches exist, delay can arise just because players fail to coordinate on one of the efficient matches.



FIGURE 5. Panel I displays the assignment economy, while panel II displays MPE agreement. The LMPE features sequential exit. As  $\lim_{\delta \rightarrow 1} q^\delta = 0$ , in the limit,  $c$  and  $d$  wait for  $a$  and  $b$  to reach an agreement before reaching an agreement themselves.

EXAMPLE 4. In Example 1, alternative matches that were lost with positive probability did not act like outside options. In Example 2 instead, alternative matches that never exited the market did act like outside options with limiting patience. The final example shows that there is another way in which matches can act as outside options without distorting trade. There can be sequential exit, in that all but one pair of players delays with probability 1 in the limit. For those players everyone else waits for, alternative matches never exit the market before them and can act like outside options.

Consider the market depicted in panel I of Figure 5. This market is vertically differentiated. Both  $b$  and  $d$  generate a higher surplus with  $a$  than  $c$ , while both  $a$  and  $c$  generate more surplus with  $b$  than  $d$ . Vertical differentiation is so strong that the match between  $a$  and  $b$  generates ten times more surplus than the match between  $c$  and  $d$ . The efficient match is assortative, and matches  $a$  to  $b$  and  $c$  to  $d$ . There is no strongly or weakly efficient MPE for  $\delta < 1$ , and no strongly efficient LMPE in this example. There is, however, a weakly efficient LMPE. For high enough  $\delta < 1$ , there exists an MPE in which player  $c$  delays with probability 1, player  $d$  agrees with  $a$  with probability  $q^\delta > 0$  and delays with probability  $1 - q^\delta$ , while  $a$  and  $b$  always agree with each other. Moreover,  $\lim_{\delta \rightarrow 1} q^\delta = 0$ , so in the limit,  $c$  and  $d$  both delay with probability 1 and wait for  $a$  and  $b$  to reach agreement before bargaining with each other. The market thus clears from the top. The limit payoffs of  $c$  and  $d$  are 5,  $a$  receives 80, and  $b$  gets 20.  $\diamond$

### 7. MPE EFFICIENCY AND FRICTIONS

We now present the main conclusions on equilibrium welfare. The analysis begins by characterizing payoffs for all efficient MPEs, and by deriving necessary and sufficient conditions for the existence of such MPEs for  $\delta$  close to 1. These conditions relate the primitives of the bargaining model to the core of the assignment economy. The second part of the section derives similar conclusions for limiting equilibria and identifies conditions under which alternative matches can serve as outside options that affect bargaining outcomes without distorting trade. Broadly speaking, the analysis establishes that inefficiency is a necessary feature of all MPEs in which players' bargaining positions evolve as others reach agreement. An efficient MPE exists only when each pair of efficiently matched players can bargain in isolation, thereby ignoring the market context,

without having a profitable deviation (outside options provided by alternative matching opportunities cannot bind). The results for limiting efficient MPEs provide the same message, but are more subtle. Agents cannot have binding *temporary outside options* provided by matching opportunities to players who may exit the market before them, but can have binding *permanent outside options* provided by matching opportunities to players who never exit the market before them.

### *Efficient equilibria and payoffs*

To state results, it is useful to introduce three relevant payoff profiles. The first of these identifies the LMPE values that players would achieve while bargaining bilaterally with their core match. For any player  $i \in N$ , let  $\sigma_i$  denote the *Rubinstein payoff* of player  $i$ ,

$$\sigma_i = \frac{p_i}{p_i + p_{\eta(i)}} s_{i\eta(i)}.$$

The second profile identifies the highest payoff that players could achieve while offering to players who are unmatched in the core of the assignment economy. For any player  $i \in N$ , let  $\omega_i$  denote the *outside payoff* of player  $i$ ,

$$\omega_i = \max_{j \in E \cup i} s_{ij}.$$

In the bargaining game, players who are unmatched in the core act as permanent outside options in efficient equilibria, as they never exit the market. The third and final profile identifies the LMPE payoffs that players would achieve while bargaining bilaterally with their core match when facing permanent outside options equal to  $\omega$  (Shaked and Sutton 1984, Sutton 1986, and Binmore and Herrero 1988). For any player  $i \in N$ , let  $\bar{\sigma}_i$  denote the *shifted Rubinstein payoff* given by

$$\bar{\sigma}_i = \begin{cases} \omega_i & \text{if } \omega_i \geq \sigma_i, \\ s_{i\eta(i)} - \omega_{\eta(i)} & \text{if } \omega_{\eta(i)} \geq \sigma_{\eta(i)}, \\ \sigma_i & \text{otherwise.} \end{cases}$$

Outside options cannot bind for both players in a core match. If they did, an alternative match that generates a weakly higher surplus would be feasible (as outside options are unmatched in the core). But, that would contradict the optimality of the core match or its uniqueness.

Although we identify necessary and sufficient conditions for the existence of an efficient MPE, it is helpful to highlight two potentially separate sources of distortions, namely inefficient matching and delay in reaching agreements. Both distortions are driven by the endogenous evolution of bargaining power that results from the random order of play. But, whereas mismatch is necessarily a hard friction since it permanently destroys surplus, delay can be a soft friction, in that its effects on welfare can become negligible when discount factors are sufficiently close to 1. [Proposition 3](#) establishes that delay cannot be the sole source of frictions in the model, as the possibility of mismatch

is necessary for delay to occur. Pinning down weakly efficient equilibria thus amounts to identifying strongly efficient equilibria. The proposition also characterizes equilibrium payoffs in any efficient MPE.

**PROPOSITION 3.** *Any weakly efficient MPE is strongly efficient. Moreover, in any subgame  $A \in C(N)$  of any weakly efficient MPE, payoffs amount to*

$$V_i(A) = \left( \frac{p_i}{(1-\delta) + \delta(p_i + p_{\eta(i)})} \right) s_{i\eta(i)} \quad \text{for all } i \in A.$$

The proof shows that players never delay in any weakly efficient equilibrium, as delay necessarily weakens their bargaining position relative to their core match. Payoffs are then derived by simple manipulations and the observation that behavior in subgames that are off the equilibrium path cannot affect the terms of trade in any equilibrium-path subgame, since players could reach such subgames only by exiting the game. As strongly efficient MPEs coincide with weakly efficient MPEs, we henceforth simply refer to them as *efficient equilibria*. Efficient MPE payoffs are stationary and independent of the set of active players along the equilibrium path, and converge to Rubinstein payoffs. When the cost of delaying is nonnegligible, bargaining is efficient only when alternative matches have no effect on outcomes and players achieve the same payoff they would get by bargaining with their efficient match in solitude.

To understand matching incentives in the model, consider the case in which delay costs are large. If so, players have a strong motive to negotiate only with their preferred bargaining partners since the cost of rejecting offers is extremely high. In this setting, equilibrium matching could be efficient only if matching with one's core partner would generate at least as much surplus as matching with any other player. Indeed, the existence of an efficient MPE requires players' preferred bargaining partners to coincide with their core partners when delay costs are large. The next remark formalizes these observations. If for some  $\varepsilon > 0$ , an efficient MPE exists for any  $\delta \in (0, 1)$  such that  $|x - \delta| \leq \varepsilon$ , we say that an efficient MPE exists *for all values of  $\delta$  close to  $x$* . A *preferred match*<sup>19</sup>  $\mu$  at an active player set  $A \subseteq N$  is a map  $\mu : A \rightarrow A$  that satisfies

$$s_{i\mu(i)} = \max_{j \in A} s_{ij} \quad \text{for all } i \in A.$$

**REMARK 1.** For all  $\delta$  close to 0, the following statements hold:

- (a) All MPEs maximize utilitarian welfare if the preferred match is unique at all  $A \subseteq N$ .
- (b) An efficient MPE exists if the core match is the unique preferred match at  $N$ .
- (c) An efficient MPE exists only if the core match is a preferred match at  $N$ .

For  $\delta$  sufficiently high, an MPE maximizes utilitarian welfare if and only if it satisfies our efficiency criterion.<sup>20</sup> However, for low  $\delta$ , this is no longer the case. When delay

<sup>19</sup>A preferred match may not be a match, as  $\mu(\mu(i)) \neq i$ .

<sup>20</sup>When  $\delta$  is close to 1, an MPE maximizes utilitarian welfare if and only if it is strongly efficient, but by Proposition 3, the set of weakly and strongly efficient MPE coincide.

costs are sufficiently high, maximizing welfare may require matching players contingent on the realization of the sequence of proposers. In particular, for sufficiently low  $\delta$ , utilitarian welfare is maximized when players agree with their preferred match, as delay costs dominate any allocative efficiency consideration.

To provide a comparison with the high  $\delta$  case and different bargaining protocols, [Remark 1\(b\)](#) provides conditions under which the core match is reached. In our directed bargaining protocol, this occurs when players' preferred match coincides with their core match; in other words, when players prefer to bargain bilaterally with their core match without negotiating with any other partner. In contrast, classical random matching models, such as [Gale and Sabourian \(2006\)](#) and [Abreu and Manea \(2012b\)](#), never implement the core match with probability 1 since, in these models, players would agree with anyone they meet when  $\delta$  is sufficiently low.

It is easy to find examples of inefficient equilibria that do not maximize welfare for intermediate costs of delay. However, inefficiencies may be driven by the large costs associated with disagreement. Indeed, one could interpret discounting as the source of matching frictions. However, the next results consider only the case in which delay costs are sufficiently small. Nevertheless, inefficiencies do not vanish.

**PROPOSITION 4.** *An efficient MPE exists for all  $\delta$  close to 1:*

(a) *If Rubinstein payoffs are in the interior of the core,*

$$\sigma_i + \sigma_j > s_{ij} \quad \text{for all } i, j \in N \text{ such that } j \neq \eta(i). \quad (2)$$

(b) *Only if Rubinstein payoffs are in the core,*

$$\sigma_i + \sigma_j \geq s_{ij} \quad \text{for all } i, j \in N.$$

[Proposition 4](#) shows that whenever Rubinstein payoffs do not belong to the core, players must agree with partners other than their core match with positive probability. When players consider agreeing with their respective core matches, the other active players act as fictitious outside options. But for these outside options to affect bargaining outcomes, these options must sometimes be exercised.<sup>21</sup> Such behavior, however, necessarily leads to mismatch, surplus dissipation, and the possibility of delay. Only when Rubinstein payoffs live in the core of the assignment economy does an efficient MPE exist.<sup>22</sup> The sufficient condition for the existence of an efficient MPE is intuitive, but does not guarantee that every Markovian equilibrium is efficient. Indeed,

<sup>21</sup>Consider again [Example 1](#), and in particular panel III of [Figure 1](#), so that  $y \in (100, 143]$ . Suppose an efficient equilibrium is played and so, by [Proposition 3](#),  $q = 1$ . A strategy available to  $b$  is to reject all offers from  $a$  and to delay when selected to propose until  $c$  and  $d$  exit the market. Doing so results in  $a$  bargaining bilaterally with  $b$  in the subsequent subgame, and in the limit,  $b$  obtains a payoff of 50. Thus, for  $a$  to receive a limiting payoff greater than 50,  $a$  must exercise his temporary outside option and inefficiently match to  $d$  with positive probability in equilibrium.

<sup>22</sup>Our result does not speak to the nongeneric case in which Rubinstein payoffs are on the boundary of the core. In such cases, a discount factor equal to 1 may be required to guarantee the existence of an efficient MPE. In Appendix B of the Supplemental Material, we show why no conclusive result is possible in such settings.

Appendix A of the Supplemental Material presents an example in which condition (2) holds, but in which multiple MPEs exist for all  $\delta$  close to 1. Coordination problems in offer strategies are the source of the multiplicity.<sup>23</sup>

**Proposition 4** establishes that bargaining inefficiencies are pervasive when negotiations are decentralized and take place in a market context (for instance, if workers' possible alternative vacancies affect the wages they are able to negotiate). In particular, the result implies that bargaining is inefficient whenever the market context matters. In other words, markets are able to clear efficiently only when all players can optimally bargain bilaterally with their efficient partners, thereby ignoring all alternatives. Moreover, these inefficiencies persist even when the discount factor is high and the exogenous frictions imposed by time preferences and sequential play become small. In **Section 8**, we explore the consequences of **Proposition 4** in classical labor market settings, and show that vertical differentiation and increasing differences are not sufficient for the existence of an efficient equilibrium.

To further explore the key conditions in **Proposition 4**, we apply the definition of Rubinstein payoffs. The existence of an efficient MPE then requires that, for all  $i$  and  $j$ ,

$$\left(\frac{p_i}{p_i + p_{\eta(i)}}\right)s_{i\eta(i)} + \left(\frac{p_j}{p_j + p_{\eta(j)}}\right)s_{j\eta(j)} \geq s_{ij}.$$

An interesting special case is when a social norm determines the bargaining power of firms relative to workers in labor markets. For instance, all agents on one side of the market may propose with the same probability  $p^1$ , while all agents on the other side do so with probability  $p^2$ . If so, the condition simplifies to

$$\left(\frac{p^1}{p^1 + p^2}\right)s_{i\eta(i)} + \left(\frac{p^2}{p^1 + p^2}\right)s_{j\eta(j)} \geq s_{ij}$$

for all  $i \in P_1$  and  $j \in P_2$ . Hence, there is an efficient MPE only if, for each worker–firm pair in the economy, a weighted average of the surplus in the worker's efficient match and in the firm's efficient match weakly exceeds the surplus that pair could generate together. Weights capture the bargaining power of workers relative to firms, and both surpluses are weighted equally when  $p^1 = p^2$ . In many cases, like **Example 1**, there do not exist any values of  $p^1$  and  $p^2$  that satisfy the above condition, implying that there is no social norm of this form that can eliminate inefficiencies.

The conclusions on efficiency have several implications, which are summarized in the next remark. These imply that (a) any core payoff can be implemented as an LMPE by appropriately selecting the vector of proposal probabilities, (b) for any pair  $\{i, \eta(i)\}$ , proportional changes in proposal probabilities cannot affect limiting bargaining outcomes, (c) efficiency is easier to achieve in economies that have a large core, and (d) any MPE without on-path delay must lead to agreement on the core match with positive

<sup>23</sup>It would be compelling to conclude by arguing that if an MPE exists for arbitrarily high and low values of  $\delta$  that implements the core match, then it also exists for any intermediate value. However, the incentive constraints that characterize such MPEs are quadratic in  $\delta$ , and this conclusion does not hold in general.

probability. For convenience, say that surpluses  $S$  support more core payoffs than  $S'$  in the strong set order if any core payoff profile in  $S'$  is also a core payoff profile in  $S$ .<sup>24</sup>

REMARK 2. The following statements are consequences of Proposition 4.

- (a) As  $\delta \rightarrow 1$ , any interior core payoff is an MPE payoff for some probabilities  $p \in \Delta(N)$ .
- (b) If an efficient MPE exists for all  $\delta$  close to 1 for probabilities  $p'$ , then it also exists for all  $\delta$  close to 1 for probabilities  $p$  such that  $p_i/p_{\eta(i)} = p'_i/p'_{\eta(i)}$  for all  $i \in N$ .
- (c) If an efficient MPE exists for all  $\delta$  close to 1 for surpluses  $S'$ , then it also exists for all  $\delta$  close to 1 for surpluses  $S$  that support more core payoffs than  $S'$ .
- (d) The core match obtains with strictly positive probability in any MPE without on-path delay.

The first part of the result implies that the closure of the set of MPE payoffs that obtain for some proposal probabilities contains the core of the assignment economy. Thus, the core can be spanned by varying proposal probabilities. As the assumptions imposed on the assignment economy imply that the interior of the core is nonempty, for any such surplus matrix it is possible to find proposer probabilities that guarantee the existence of an efficient MPE. By interpreting players' proposal probabilities as their bargaining power, the second part shows that when delay costs are small, a player's bargaining power matters only relative to that of his efficient match in any efficient MPE. The third part implies that economies with larger cores are more likely to result in efficient bargaining outcomes. The final part obtains because in any MPE without on-path delay, it is impossible to find a subset of players who prefer to exchange their respective core matches. Hence, some players must optimally agree with their efficient match. However, as we saw in Examples 3 and 4, on-path delay can occur in equilibrium and the no-delay condition is nontrivial.<sup>25</sup>

### *Limiting efficiency*

Efficient LMPE may differ considerably from efficient MPE. Proposition 4 considers only  $\delta < 1$  and, therefore, categorizes as inefficient any equilibrium in which mismatch occurs with a vanishingly small probability as  $\delta$  converges to 1. Moreover, Examples 2 and 4 establish that mismatch can occur in equilibrium with vanishingly small probability. This section studies this possibility and analyzes under which conditions inefficiencies can be small in this sense.

The first result of this section extends Proposition 3, showing that strongly efficient LMPEs converge to shifted Rubinstein payoffs. Whenever these payoffs differ from Rubinstein payoffs and delay is costless, unmatched players in  $E$  can act as permanent

<sup>24</sup>For instance,  $S$  supports more core payoffs than  $S'$  if, for all  $i \in N$ ,  $s_{ij} = s'_{ij}$  whenever  $j = \eta(i)$  and  $s_{ij} \leq s'_{ij}$  whenever  $j \neq \eta(i)$ .

<sup>25</sup>We stress again that Example 2 does not fit our definition of equilibrium delay, since in the unique LMPE, the only player who delays has a continuation value equal to zero.

outside options without distorting the limiting equilibrium match. In [Example 2](#), for instance, player  $c$  had an effect on player  $f$ 's terms of trade in the limit without ever matching to  $f$ . The result also extends the negative efficiency conclusions of [Proposition 4](#) to markets in which delay costs vanish. In the limit, equilibria cannot be efficient if shifted Rubinstein payoffs are outside the core of the assignment economy.

**PROPOSITION 5.** *In any strongly efficient LMPE, the payoff of any player  $i \in A$  in any equilibrium-path subgame  $A \in C(N)$  converges to*

$$\lim_{\delta \rightarrow 1} V_i(A) = \bar{\sigma}_i.$$

*Moreover, a strongly efficient LMPE exists only if shifted Rubinstein payoffs are in the core,*

$$\bar{\sigma}_i + \bar{\sigma}_j \geq s_{ij} \quad \text{for all } i, j \in N.$$

Core unmatched players can affect the limiting terms of trade without ever agreeing, because they belong to every equilibrium-path subgame. Core matched players instead cannot play such a role in a strongly efficient LMPE as, in the limit, they exit the game at the first available opportunity by agreeing with their core match. In addition to demonstrating the robustness of the conclusions previously reached, [Proposition 5](#) uncovers a crucial difference between temporary alternative matches that can be lost as the market evolves and permanent alternative matches that cannot be lost as the market evolves. We term the former *temporary outside options* and the latter *permanent outside options*. Furthermore, the result clarifies why bargaining frictions arise endogenously as a strategic response to possible changes in the market composition. It is the concern about an alternative match exiting the market, thereby weakening the bargaining position of a player, that induces this player to agree with an inefficient partner even when  $\delta$  converges to 1. As we have seen in [Example 3](#), similar considerations regarding the evolution of the market can also lead to delay on the equilibrium path.

When shifted Rubinstein payoffs are in the interior of the core, they coincide with Rubinstein payoffs by construction. If so, by [Proposition 4](#), an efficient equilibrium exists for any sufficiently high value of  $\delta$  and, thus, a strongly efficient LMPE exists in this case. Strongly efficient LMPE may also exist even when shifted Rubinstein payoffs are on the boundary of the core, as was the case in [Example 2](#). If so, distortions vanish only when the discount factor approaches 1.

Next, we consider weakly efficient LMPE and their properties. The main result establishes that, whereas only core unmatched players can act as permanent outside options in strongly efficient LMPE, all players can potentially act as permanent outside options in some weakly efficient LMPE. However, for this to be the case, the market must clear sequentially, one core match at a time. If so, even players who are ultimately matched can act as permanent outside options by matching only after some other players have matched. To formalize the discussion, it is convenient to introduce a notion of sequential agreement.



DEFINITION 6. A weakly efficient LMPE is a sequential LMPE if for some  $A \in C(N)$  such that  $|A \setminus E| \geq 4$  and for some  $i \in A \setminus E$ ,

$$\lim_{\delta \rightarrow 1} \pi_{jj}(A) = 1 \quad \text{for any } j \in A_{-i\eta(i)}. \tag{3}$$

Sequential LMPEs display sequential agreement in that all players in the market, except for one pair, delay reaching an agreement until that pair has exited the market. Sequential equilibria require extensive delay to occur despite delay being costly. In particular, pairs who eventually are matched with probability 1 have to prefer to delay instead of reaching agreement with each other, even though doing so reduces the value of any agreement they can reach. None of the earlier literature, including the examples in Gale and Sabourian (2006) and Abreu and Manea (2012b), features sequential agreement.

The next result establishes that any weakly efficient LMPE whose limiting payoffs do not converge to shifted Rubinstein payoffs must be sequential. Two LMPE are said to be *payoff equivalent* if the ex ante limiting values coincide in the two equilibria for all players.

PROPOSITION 6. *Any weakly efficient LMPE that is not payoff equivalent to a strongly efficient LMPE is sequential. Moreover, sequential LMPE exist in some markets.*

An important and immediate implication of Proposition 6 is that when shifted Rubinstein payoffs are outside of the core, either there is no efficient LMPE or all efficient LMPE are sequential.<sup>26</sup> Proposition 6 therefore helps to pin down the contexts in which weakly efficient LMPE exist. When exit is sequential, all players remain in the market until a given core match exits, thereby acting effectively as permanent outside options for this match. Proposition 6 further reinforces our central message that inefficiencies are ubiquitous. Indeed, even in a weakly efficient LMPE, outside options cannot affect bargained outcomes without being exercised with strictly positive probability, given that they are temporary and can be lost on the equilibrium path. Nevertheless, people who are efficiently matched can provide outside options that are effectively permanent through sequential exit. Although Proposition 6 does not characterize weakly efficient LMPE payoffs, insights in its proof suggest that it should be possible to derive a (not very tractable) payoff set that necessarily contains all weakly efficient LMPE payoffs.<sup>27</sup> If so,

<sup>26</sup>By Proposition 5, if a LMPE is payoff equivalent to a strongly efficient LMPE, it must generate shifted Rubinstein payoffs. But if these payoffs are outside of the core, at least one player has a strict incentive to offer to an inefficient partner.

<sup>27</sup>To do so, consider any subset of players  $M \in P_1 \setminus E$  (where  $m = |M|$ ), and consider any order over these players,  $M = \{o(1), \dots, o(m)\}$  (where  $o(i)$  identifies the  $i$ th ranked player in  $M$ ). Define the Rubinstein chain payoffs associated with this order  $o$  and this subset  $M$  as a payoff profile  $u \in \mathbf{R}^{2m}$  (for players in  $M$  and their respective core partners) such that

$$u_{o(1)} = \bar{\sigma}_{o(1)}, \quad u_{\eta(o(i))} = s_{o(i)\eta(o(i))} - u_{o(i)} \quad \text{for } i \geq 1,$$

$$u_{o(i)} = s_{o(i)\eta(o(i-1))} - u_{\eta(o(i-1))} \quad \text{for } i > 1.$$

For any partition of  $P_1 \setminus E$  and for any associated order for each element of the partition, define the collection of Rubinstein chain payoffs as a payoff vector in  $\mathbf{R}^n$  such that (i) in every element of the partition,

by the same logic of Proposition 4, no weakly efficient LMPE would exist whenever such a set does not intersect the core.

It is intriguing that sequential exit can occur in equilibrium. The observation conforms with empirical regularities in some matching markets that can clear from the top down. However, delay is a knife-edge phenomenon in most bargaining models without asymmetric information. It might be thought that the existence of a sequential LMPE requires very specific parameter restrictions on the bargaining problem. To address this issue systematically, we conclude by characterizing the set of sequential LMPEs in the context of a four-player market with equal proposer probabilities. Let  $N = \{a, b, c, d\}$  and  $p_i = p$  for  $i \in N$ . To avoid redundancies when stating results, we adopt the following labeling convention:

- The matches  $ab$  and  $cd$  denote the core matches, that is,  $s_{ab} + s_{cd} > s_{ad} + s_{bc}$ .
- The match  $ab$  denotes the most valuable core match, that is,  $s_{ab} \geq s_{cd}$ .
- The match  $ad$  denotes the most valuable non-core match, that is,  $s_{ad} \geq s_{bc}$ .

We also omit the dependence on  $N$  when it is obvious. The final result on efficient LMPEs characterizes payoffs in a sequential LMPE, and delivers necessary and sufficient conditions for the existence of such an LMPE.

REMARK 3. Given our convention, if a sequential LMPE exists, then for all  $\delta$  close to 1,

$$\pi_{ab} = \pi_{ba} = \pi_{cc} = \pi_{da} + \pi_{dd} = 1, \quad \pi_{da} > 0, \quad \text{and} \quad \lim_{\delta \rightarrow 1} \pi_{dd} = 1.$$

Moreover, in any such LMPE,

$$\begin{aligned} \lim_{\delta \rightarrow 1} V_a &= s_{ad} - \sigma_d, & \lim_{\delta \rightarrow 1} V_c &= \sigma_c, \\ \lim_{\delta \rightarrow 1} V_b &= s_{ab} - s_{ad} + \sigma_d, & \lim_{\delta \rightarrow 1} V_d &= \sigma_d. \end{aligned}$$

Finally, a sequential LMPE exists if and only if

$$s_{ab} > s_{ad} > \frac{s_{ab} + s_{cd}}{2} > s_{bc} > s_{cd} \quad \text{and} \quad \frac{s_{bc} - s_{cd}}{2(s_{ab} - s_{ad})} \geq \frac{s_{bc} + s_{cd}}{s_{ab} + s_{cd}}. \tag{4}$$

The remark pins down agreement probabilities at a high frequency of interaction in any sequential LMPE. In such equilibria, players  $a$  and  $d$  always reach agreement before  $c$  and  $d$ . As  $c$  and  $d$  end up bargaining bilaterally with each other, they have limit payoffs equal to their Rubinstein payoffs. Thus, when players  $a$  and  $d$  are bargaining, it is as if  $a$  had a permanent outside option of value  $s_{ad} - \sigma_d$ . Since  $s_{ad} - \sigma_d > \sigma_a$ , this outside options binds and  $a$  gets a limit payoff of  $s_{ad} - \sigma_d$ , leaving  $b$  with the residual surplus

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payoffs correspond to the chosen Rubinstein chain payoffs, and (ii) players in  $E$  get nothing. Take the union over all partitions of  $P_1 \setminus E$  and take the union over all possible orders for each element of the chosen partition. Define such a payoff set by  $\Psi$ . Our conjecture is that in any weakly efficient LMPE, payoffs must belong to  $\Psi$ .

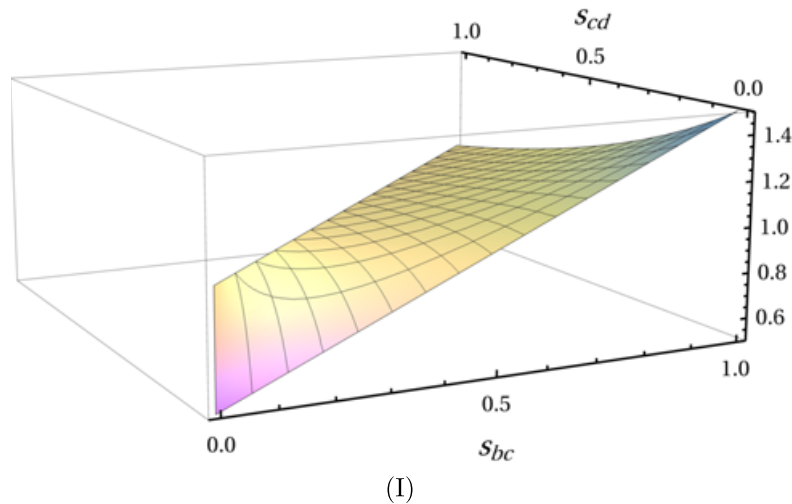


FIGURE 6. Plot of the lower bound for  $\zeta$  for different combinations of  $s_{cd}$  and  $s_{bc}$ . As  $\zeta < 1$ , regions of the parameter space where the lower bound is greater than 1 are regions in which no sequential LMPE exists.

$s_{ab} - (s_{ad} - \sigma_d)$ .<sup>28</sup> This equilibrium conforms to previous intuitions: alternatives within the market can affect the terms of trade only if they remain in the market indefinitely.

The conditions in (4) have natural interpretations. Given our labeling conventions, the requirement  $s_{ab} > s_{ad} > s_{bc} > s_{cd}$  implies that the market must be vertically differentiated. Moreover, the first match to reach agreement is the most valuable core match. We therefore rationalize top-down sequential exit as a limiting efficient market outcome in a complete information decentralized bargaining game. Delay in bargaining is hard to get, but real world experience suggests that matching markets can occasionally be held up while clearing from the top. Our model delivers such behavior as an equilibrium phenomenon in thin markets without any asymmetric information. The second condition in (4) requires  $s_{ad} > (s_{ab} + s_{cd})/2$ , or, equivalently,  $s_{ad} > \sigma_a + \sigma_d$ . This condition implies that shifted Rubinstein payoffs are outside of the core. As a consequence, by Proposition 5, there is no strongly efficient LMPE, and by Proposition 6, any weakly efficient LMPE must be sequential.

The final condition in (4) is the hardest to interpret. Although payoffs must be supermodular by the first part of (4), they cannot be log supermodular by the second part of (4). Log supermodularity in this context requires that  $s_{ab}s_{cd} \geq s_{ad}s_{bc}$ , and the final condition in (4) rules this out.<sup>29</sup> In combination with the other conditions, it requires

<sup>28</sup>In effect,  $b$  also has a permanent outside option worth  $s_{bc} - \sigma_c$ . However, this outside option does not bind. Payoffs are thus pinned down by chains of outside options in any sequential LMPE. These chains are evocative of those discussed in Elliott (2015).

<sup>29</sup>The second part of condition (4) can be rewritten as

$$2(s_{ad}s_{bc} - s_{ab}s_{cd}) \geq s_{cd}(s_{ab} + s_{cd} - s_{bc} - s_{ad}) + s_{ab}(s_{bc} - s_{cd}) > 0.$$

the market to be highly vertically differentiated such that the proportion of surplus generated by the worst match relative to the best match,  $s_{cd}/s_{ab}$ , is small. To see this, it is instructive to consider the potential extent of mismatch inefficiencies in the assignment economy (which also captures how supermodular surpluses are). For convenience, normalize  $s_{ab} = 1$  and define the fraction of potential surplus that is obtained by mismatching as  $\zeta = (s_{ad} + s_{bc})/(1 + s_{cd}) \in (0, 1)$ . The final and key restriction to the parameter space given in [Remark 3](#) can then be restated in terms of this parameter as requiring

$$\zeta \geq \frac{2(1 + s_{bc})(s_{bc} + s_{cd}) - (1 + s_{cd})(s_{bc} - s_{cd})}{2(s_{bc} + s_{cd})(1 + s_{cd})}.$$

We plot this lower bound on the relative efficiency of the wrong matches in [Figure 6](#). The plot shows that when  $s_{cd}$  is relatively large, there is no sequential LMPE. More precisely, there is a sequential LMPE only if  $s_{cd} < 1 - 2s_{bc}$ . Since by [Remark 3](#),  $s_{bc} > s_{cd}$ , a sequential LMPE exists only if  $s_{cd}/s_{ab} < 1/3$ . Hence, the less productive core match must be at least three times less productive than the most productive core match. This upper bound on the relative value of  $s_{cd}$  becomes much tighter when the potential loss  $\zeta$  associated with mismatch is at least 5%. Indeed, for  $\zeta \leq 0.95$ , a similar calculation establishes that  $s_{cd}/s_{ab} < 0.133$ . Therefore,  $s_{cd}$  can be at most 13.3% as productive as  $s_{ab}$ .<sup>30</sup> We conclude that sequential LMPEs exist only in sufficiently vertically differentiated markets and only in extremely differentiated markets if mismatch generates a considerable amount of inefficiency.

## 8. DISCUSSION

### *Assortative matching*

The labor market search literature has extensively studied a particular form of heterogeneity—vertically differentiated markets with assortative matching—as in, for instance, [Shimer and Smith \(2000\)](#), [Eeckhout \(2006\)](#), [Smith \(2006\)](#), and [Eeckhout and Kircher \(2010\)](#). To appreciate the content of our efficiency implications, we consider this special case of our model.

It is convenient to introduce some new notation. For this section, we refer to the two sides of the market as workers and firms. Let  $W = \{1, \dots, w\}$  and  $F = \{1, \dots, f\}$  denote the sets of workers and firms, respectively, and let the surplus generated by worker  $i$  and firm  $j$  be given by a function  $S : W \times F \rightarrow \mathbb{R}_+$  satisfying the conditions

$$(A1) \quad S(i, j) > S(i', j) \text{ if and only if } i < i'$$

$$(A2) \quad S(i, j) > S(i, j') \text{ if and only if } j < j'$$

$$(A3) \quad S(i, j) - S(i, j') > S(i', j) - S(i', j') \text{ if and only if } i < i' \text{ and } j < j'.$$

Condition (A1) requires workers to be vertically differentiated, (A2) requires firms to be vertically differentiated, and (A3) requires increasing differences in the surpluses that

<sup>30</sup>[Example 4](#) in [Section 6](#) provides some specific parameter values for which sequential exit occurs. In this example,  $s_{cd}/s_{ab} = 0.1$  and  $\zeta = 0.955$ .

worker–firm pairs can generate. Surplus is generated only in matches between workers and firms. In contrast to our previous notation, there can now be a worker type  $i$  and a firm type  $i$ . Thus typically  $S(i, i) \neq 0$  and  $S(i, j) \neq S(j, i)$  unless the surplus generated by the  $i$ th ranked worker matching to the  $j$ th ranked firm is the same as the surplus generated by  $j$ th ranked worker matching to the  $i$ th ranked firm. Let the set of functions satisfying these conditions be denoted by  $\bar{S}$ . It is well known that in such markets, the unique core match is the assortative match in which worker  $k$  is matched to firm  $k$  if  $k \leq \min\{w, f\}$ , while all the remaining agents are unmatched.

We use our efficiency results to find conditions under which decentralized bargaining would result in an efficient and thus assortative match. For convenience, let the vector  $p$  denote the proposal probabilities of firms, where entry  $p_k$  is the proposal probability of firm  $k$ . Analogously, let  $q$  denote the proposal probabilities of workers, where entry  $q_k$  is the proposal probability of worker  $k$ . Thus, a vertically differentiated market is defined by the tuple  $\{W, F, S, p, q\}$ .

**REMARK 4.** If  $w = f$ ,  $p_k = q_k = p$  for all  $k \leq \max\{w, f\}$ , and  $S(i, j) = S(j, i)$  for all  $i, j \leq \min\{w, f\}$ , then for all  $\delta$  close to 1, there is an efficient MPE. However, if at most two of these three conditions hold, there exists a vertically differentiated market for which there is no weakly efficient LMPE.

**Remark 4** shows that, although there are natural conditions under which there is a strongly efficient MPE (the strongest efficiency criterion of the four we consider), these conditions are fairly restrictive and require the market to be highly symmetric. There must be the same number of workers as firms, the  $k$ th ranked worker and firm must have the same proposal probabilities, and the surplus generated by the  $i$ th ranked worker matching to the  $j$ th ranked firm must be the same as the surplus generated by the  $j$ th ranked worker matching to the  $i$ th ranked firm. When any one of these conditions is not satisfied, there are surpluses  $S \in \bar{S}$  for which there is no weakly efficient LMPE (the weakest efficiency criterion of the four we consider).

### *Random matching*

The directed search matching protocol considered in our analysis was chosen to minimize frictions. To appreciate the pure delay frictions that arise when players cannot choose whom to bargain with, consider the eight-player line network shown in [Figure 7](#). We provide a brief discussion of such inefficiencies as a means of comparison to our model. A comprehensive analysis of the example appears in Section 4 of [Abreu and Manea \(2012b\)](#).

Suppose that matching opportunities are as shown in [Figure 7](#) and that each link is selected with equal probability. An efficient LMPE requires players to disagree with a probability that converges to 1 whenever links  $bc$ ,  $de$ , or  $fg$  are selected. For this to be the case, the combined continuation values from disagreement of the two players on the link must exceed 1 in the limit or converge to 1 from above. With the random matching protocol, efficient LMPEs exist in the line networks with four or six players. But this is not

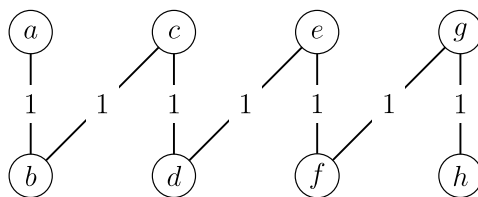


FIGURE 7. The eight-player line network.

the case in the line network with eight players. In a four-player line network, the two end players are weak since they get no surplus when the middle players agree. For all  $\delta$  sufficiently high, there is an MPE in which the two middle players agree with a vanishingly small probability, and doing so reduces the continuation values of the end players to the point where the middle players are indifferent between delaying and agreeing with each other. With eight players, this no longer works. In such networks, players  $d$  and  $e$  disagree when initially matched. Despite this, their bargaining positions improve relative to the four-player line network as they retain the option to agree with each other in subgames in which their core partners exit. Consequently, players  $b$  and  $c$  strictly prefer to agree if they are initially matched for sufficiently high values of  $\delta$ . [Abreu and Manea \(2012b\)](#) establish in fact that, in the unique LMPE, players  $b$  and  $c$  must inefficiently agree with probability 1 when matched, even when delay costs vanish. If, instead, players were selected to propose with equal probability and were able to choose with whom to agree, a strongly efficient MPE would always exist as shown in Proposition 7 in the Supplemental Material.

Preventing players from choosing bargaining partners amplifies frictions, since players have to either hold out for their desired partner when presented with an alternative matching opportunity or agree with inefficient partners. We opted for a setting in which players were allowed to choose bargaining partners to diminish the holdup frictions associated to waiting for the preferred match. Yet, we still found frictions to be a common feature of decentralized negotiations because of nonstationarities in the evolution of bargaining power.

#### *Limitations and evidence*

We study the Markov perfect equilibria of a simple bargaining game with many buyers and many sellers, seeking necessary and sufficient conditions for the existence of efficient Markov perfect equilibria. Necessary conditions, however, do not rule out the existence of efficient non-Markovian equilibria,<sup>31</sup> while sufficient conditions do not rule out the existence of inefficient Markov perfect equilibria.<sup>32</sup>

Our protocol is fairly standard and chosen to give the best chance to efficient outcomes while remaining decentralized. To this end, we allow the proposer to choose to

<sup>31</sup>An efficient subgame perfect equilibrium may always exist, as proven by [Abreu and Manea \(2012a\)](#) for networks with homogeneous surpluses.

<sup>32</sup>We show in Appendix A of the Supplemental Material that inefficient MPEs can coexist with efficient MPEs.

whom to offer, study the generic case in which the efficient match is unique, and look at equilibria in which delay costs are small. A key feature of our model is that players' bargaining positions (and, more precisely, their limit payoffs) can change stochastically. We find that these non-stationarities in the evolution of bargaining power are closely linked to inefficiencies, which can include both mismatch and delay. In all weakly efficient LM-PEs, players' limit payoffs are stationary on the equilibrium path and do not depend on the order in which people are selected to propose. This can occur for several reasons. First, no alternative match might provide a binding alternative ([Proposition 3](#)). Second, binding alternative matches might only be provided by those who are unmatched when the market clears efficiently ([Proposition 4](#)). Finally, there might be sequential exit and the market endogenously remains stationary while all players wait for a given pair to exit the market before reaching agreements themselves ([Proposition 5](#)).

While we view our protocol as natural, many alternative bargaining protocols are equally reasonable. For instance, random matching protocols may describe players bumping into each other at random, while the protocol we study might be a better fit for thin, highly heterogeneous markets, in which everyone knows everyone else, and in which search is more likely to be directed. It is not clear whether similar results would hold in the alternative model with random matching. On the one hand, in the limit, incentives look very similar to our model, but on the other hand, away from the limit, random matching forces players to forgo matching inefficiently but immediately so as to match to their efficient partner later on. There are many other alternative protocols. One would be to include the right to make a counteroffer back to the proposer. Another one would designate a player declining an offer to be the new proposer. Yet another alternative would fix a predetermined and commonly known proposer order. We would not expect results close to ours to hold in these environments, since from a strategic point of view, these environments seem to be fundamentally different.

In practice, interactions in markets are unlikely to be as constrained as any of these bargaining protocols. Furthermore, players are likely to have much more freedom to endogenously determine, among other things, who moves when. Indeed, we show that there always exist offer probabilities that generate efficient outcomes. If these are endogenously determined, then efficiency might be improved or even restored. Nevertheless, while norms might evolve to affect offer probabilities and increase efficiency, they would need to be tailored to the intricacies of a given market to eliminate inefficiencies (see the discussion following [Proposition 4](#)). Fully endogenizing the timing of offers would come at the cost of tractability. The value of simple theory comes from its ability to provide useful insights in richer settings. Whether our theory, including the equilibrium selection, obtains this goal is ultimately an empirical question.

While identifying mismatch empirically is hard because counterfactual productivities are not directly observed, Agranov and Elliott (2017) run a laboratory experiment to circumvent this issue. They begin by studying an experimental protocol that mirrors our bargaining protocol. They find extensive inefficiencies, and show that the Markov perfect equilibrium outcomes correctly predict which markets exhibit mismatch and which exhibit more mismatch than others. However, inefficient matches occur considerably

more often than predicted.<sup>33</sup> They then run a second laboratory experiment, but without an experimental protocol. Participants are permitted, at any time, to make offers to anyone else, accept offers they have received, and withdraw offers they have made. They find that inefficiencies remain in the market.<sup>34</sup> In this experiment, there is not sufficient evidence to reject that inefficiencies are different from the MPE predictions at the 5% level. While this should not be interpreted as evidence that players play the MPEs of our bargaining game in an entirely different bargaining environment, it does suggest that in more realistic bargaining situations, the inefficiencies we document remain and that the MPEs provide useful intuitions.<sup>35</sup>

#### APPENDIX: PROOFS

**PROOF OF PROPOSITION 1.** We first establish the characterization of MPE values and then proceed to establish existence. Fix a discount factor  $\delta \in (0, 1)$ . Consider an MPE strategy profile  $(\rho, \chi, \alpha)$  and its corresponding MPE payoffs  $V(A) \in \mathbb{R}^{|A|}$  for any active player set  $A \subseteq N$ . Fix any subset  $A \subseteq N$ . By subgame perfection, we know that the acceptance decision by a player  $j \in A$  faced with an offer  $x$  must be such that he accepts an offer if  $x > \delta V_j(A)$ , and rejects it if  $x < \delta V_j(A)$ . Clearly, this implies that it cannot be optimal to offer  $x > \delta V_j(A)$  to player  $j$ , as the proposer could profitably deviate to an offer in  $(\delta V_j(A), x)$ . Thus, in any MPE, every player would offer at most  $\delta V_j(A)$  to player  $j$ , and the only offers player  $j$  may accept with positive probability are offers of  $\delta V_j(A)$ . Therefore, a proposer  $i \in A$  would make offers with positive probability only to a player  $j$  that maximizes his residual payoff  $s_{ij} - \delta V_j(A)$ . Recall that  $\pi_{ij}(A)$  is the joint probability that player  $i$  offers  $\delta V_j(A)$  to player  $j$  and that the offer is accepted, and that  $\pi_{ii}(A)$  is the joint probability that  $i$  does not agree when proposing. We frequently abuse notation by dropping the dependence of  $\pi_{ij}$  on  $A$  where it should not cause confusion. The payoff of any player  $k \in A_{-ij}$  at the beginning of the following period is given by  $V_k(A_{-ij})$  if an agreement was reached and by  $V_k(A)$  otherwise. Therefore, at a history in which the set of active players is  $A$  and in which  $i$  is the proposer, the expected payoff of a player  $k \in A_{-i}$  must be given by

$$\sum_{j \in A_{-ik}} \pi_{ij} \delta V_k(A_{-ij}) + \left(1 - \sum_{j \in A_{-ik}} \pi_{ij}\right) \delta V_k(A).$$

When  $i$  is chosen to propose, if  $\delta[V_i(A) + V_j(A)] < s_{ij}$  for some  $j \in A_{-i}$ , then  $i$  offers with certainty to players  $j$  who maximize  $s_{ij} - \delta V_j(A)$ , and agreement obtains with certainty. The latter observation obtains from the following argument. If  $\pi_{ii} > 0$ , then the expected

<sup>33</sup>Across the three networks they consider, the MPEs predict inefficient matches to occur with probabilities 0%, 28%, and 50%, respectively. In the experimental data, there is mismatch with probabilities 0%, 49%, and 70%, respectively, across the networks.

<sup>34</sup>They are positive at the 5% level.

<sup>35</sup>We have argued that inefficiencies in our model are driven by the changing composition of the market. This suggests that allowing people to rematch might reduce or eliminate inefficiencies. Arganov and Elliott (2017) also test this conjecture and find some support for it.



payoff conditional on offering  $\delta V_j(A)$  to players  $j$  who maximize  $s_{ij} - \delta V_j(A)$  amounts to

$$\sum_{j \in A_{-i}} \pi_{ij}(s_{ij} - \delta V_j(A)) + \left(1 - \sum_{j \in A_{-i}} \pi_{ij}\right) \delta V_i(A)$$

and must be strictly smaller than  $s_{ij} - \delta V_j(A)$ . The payoff conditional on  $i$  offering  $\delta V_j(A) + \varepsilon$  to  $j$  for  $\varepsilon > 0$  is  $s_{ij} - \delta V_j(A) - \varepsilon$ , as  $j$  accepts with probability 1 any offer exceeding  $\delta V_j(A)$ . Hence, it cannot be optimal to offer more than  $\delta V_j(A)$ . It also cannot be optimal to offer less than  $\delta V_j(A)$  since all such offers are rejected and since  $\delta V_i(A) < s_{ij} - \delta V_j(A)$ . Thus, if  $\pi_{ii} > 0$  and  $\delta[V_i(A) + V_j(A)] < s_{ij}$ , a profitable deviation always exists. Therefore,  $\delta[V_i(A) + V_j(A)] < s_{ij}$  for some  $j \in A_{-i}$  implies  $\pi_{ii} = 0$ . Similarly,  $\delta[V_i(A) + V_j(A)] > s_{ij}$  for any  $j \in A_{-i}$  implies  $\pi_{ii} = 1$ . If  $\max_{j \in A_{-i}} \{s_{ij} - \delta[V_i(A) + V_j(A)]\} = 0$ , then  $\pi_{ii} \in [0, 1]$ . Thus, any agreement probability  $\pi_i \in \Delta(A)$  for player  $i$  compatible with equilibrium values  $V \in \mathbb{R}^{|A|}$  must belong to

$$\Pi(V|A, i) = \left\{ \pi_i \in \Delta(A) \mid \begin{cases} \pi_{ii} = 0 \text{ if } \delta V_i < \max_{j \in A_{-i}} \{s_{ij} - \delta V_j\} \\ \pi_{ik} = 0 \text{ if } s_{ik} - \delta V_k < \max \left\{ \delta V_i, \max_{j \in A_{-i}} \{s_{ij} - \delta V_j\} \right\} \end{cases} \right\}.$$

At any history in which  $A$  is the set of active players and  $i \in A$  is the proposer, define a function  $\bar{u}(V, \pi|A, i) : \mathbb{R}^{|A|} \times \Delta(A) \rightarrow \mathbb{R}^{|A|}$  that identifies, for every player in  $A$ , the expected payoff compatible with our partial equilibrium analysis when the agreement probabilities are  $\pi_i \in \Pi(V|A, i)$  and continuation values are  $V \in \mathbb{R}^{|A|}$ :

$$\bar{u}(V, \pi_i|A, i) = \begin{cases} (1 - \pi_{ii}) \max_{j \in A_{-i}} \{s_{ij} - \delta V_j\} + \pi_{ii} \delta V_i & \text{if } k = i, \\ \sum_{j \in A_{-ik}} \pi_{ij} \delta V_k(A_{-ij}) + (\pi_{ik} + \pi_{ii}) \delta V_k & \text{if } k \neq i. \end{cases}$$

Next consider the correspondence  $u(V|A, i) : \mathbb{R}^{|A|} \rightrightarrows \mathbb{R}^{|A|}$  that identifies the set of expected payoffs compatible with our analysis for continuation values  $V \in \mathbb{R}^{|A|}$ :

$$u(V|A, i) = \{W \in \mathbb{R}^{|A|} \mid W = \bar{u}(V, \pi_i|A, i) \text{ for } \pi_i \in \Pi(V|A, i)\}.$$

Finally, consider the correspondence  $U(V|A) : \mathbb{R}^{|A|} \rightrightarrows \mathbb{R}^{|A|}$  that identifies the set of possible expected payoffs at any history in which  $A$  is the set of active players:

$$U(V|A) = \sum_{i \in A} p_i u(V|A, i) + \left(1 - \sum_{i \in A} p_i\right) \delta V. \tag{5}$$

Our arguments establish that  $V$  is an MPE payoff only if it is a fixed point of the correspondence in (5),  $V \in U(V|A)$ .

Next we establish that the converse must hold too. In particular, we argue that if  $V(A) \in U(V(A)|A)$  for any subset  $A \subseteq N$ , then  $V(A)$  is an MPE payoff profile for any subgame in which  $A$  is the set of active players. At any subgame in which  $A$  is the

set of active players, consider a strategy in which any player  $i \in A$  chooses  $\rho_i(A) = \pi_i$ ,  $\chi_i(j, A) = \delta V_j(A)$ , and

$$\alpha_i(j, x, A) = \begin{cases} 1 & \text{if } x \geq \delta V_i(A), \\ 0 & \text{if } x < \delta V_i(A). \end{cases}$$

For any finite set of players  $N$ , the proposed strategy clearly must be an MPE in any subgame in which no more than one player is active, as any such subgame is eventless. By induction, suppose that the proposed strategy is an MPE for any subset of active players of size  $k \leq n - 1$ , so as to show that it is an MPE for any subgame in which the set of active players has size  $k + 1$ . Consider a subgame in which the set of active players  $A$  has cardinality  $k + 1$ . Fix an MPE payoff profile  $V(A')$  for all subgames in which the cardinality of the set of active players  $A'$  does not exceed  $k$ . Furthermore, given such values, suppose that we can find a payoff profile  $V(A)$  such that  $V(A) \in U(V(A)|A)$  (we establish below that such a fixed point exists). If so, no player receiving an offer can profitably deviate from strategy  $\alpha$ , since no change in the acceptance rule can strictly increase the payoff. Similarly, given the acceptance rule, the proposer's strategy  $(\rho, \chi)$  is optimal given that offers are made only to those players who leave the highest residual surplus to the proposer (provided that such surplus exceeds the value of being unmatched). Thus,  $V(A)$  is an MPE payoff in any subgame with a set of active players  $A$ . Consequently, if  $V(A) \in U(V(A)|A)$  for any subset  $A \subseteq N$ , then  $V(A)$  is an MPE payoff profile.

To establish existence, proceed by induction. Existence follows in subgames in which no more than one player is active, as such subgames are eventless. Assume by induction that an MPE exists for any subset of active players of size  $k \leq n - 1$ , so as to show that it exists for any subgame in which the set of active players  $A$  has size  $k + 1$ . If so, consider MPE strategies for all subgames of size  $k$  and derive MPE payoffs for all such subgames. Given such values, construct the correspondence  $U(\cdot|A)$  as in (5). Observe that the correspondence  $\Pi(\cdot|A, i)$  is upper hemicontinuous with nonempty convex images. Thus,  $u(\cdot|A, i)$  is upper hemicontinuous with nonempty convex images, and so the correspondence  $U(\cdot|A)$  is upper hemicontinuous with nonempty convex images, as it is a convex combination of the correspondences  $u(\cdot|A, i)$  for  $i \in A$ . By Kakutani's fixed point theorem,  $U(\cdot|A)$  has a fixed point. Moreover, such a fixed point is an MPE payoff of this subgame, and can be used to construct consistent MPE strategies and, consequently, agreement probabilities  $\pi_i \in \Delta(A)$  for all proposers  $i \in A$  in every subgame  $A$ , as argued above.  $\square$

**PROOF OF PROPOSITION 2.** For convenience, define the limiting agreement probability for a given player  $j \in A \setminus E$  as  $\beta_j(A) = \lim_{\delta \rightarrow 1} p_j \pi_{j\eta(j)}(A)$ , and let  $\beta_B(A) = \sum_{k \in B} \beta_k(A)$  for any  $B \subseteq A$ . Recall that  $\bar{V}_j(A) = \lim_{\delta \rightarrow 1} V_j(A)$ . We begin by showing that for any active player set  $A \in C(N)$  such that  $A \setminus E \neq \emptyset$ , there exists a player  $i \in A \setminus E$  such that  $\beta_i(A) > 0$ . This is the case since weak efficiency and  $\beta_i(A) = 0$  for all player  $i \in A \setminus E$  imply  $\bar{\pi}_{ii}(A) = 1$  for all players  $i \in A \setminus E$ . But, if so, for  $\delta$  close to 1, any player  $i$  would weakly prefer delaying to offering to  $\eta(i)$  or, equivalently,

$$\delta V_i(A) + \delta V_{\eta(i)}(A) \geq s_{i\eta(i)}. \tag{6}$$

This would lead to a contradiction though as the sum of payoffs exceeds total surplus

$$\sum_{i \in A} V_i(A) \geq \sum_{i \in A \setminus E} V_i(A) \geq (1/\delta) \sum_{i \in A \cap P_1} s_{i\eta(i)} > \sum_{i \in A \cap P_1} s_{i\eta(i)},$$

where the first and third inequalities are trivial while the second holds by adding the inequalities in (6) and observing that  $s_{i\eta(i)} = 0$  if  $i \in E$ . Thus, in any nontrivial active player set  $A \in C(N)$  of any weakly efficient LMPE, there exists a player  $i \in A \setminus E$  such that  $\beta_i(A) > 0$ .

To prove the result, we proceed by induction on the size of the active player set within  $C(N)$ . We show that, in any weakly efficient LMPE,  $\bar{V}_i(A) + \bar{V}_{\eta(i)}(A) = s_{i\eta(i)}$  for any  $i \in A \setminus E$  and any  $A \in C(N)$ . The latter then immediately implies surplus maximization by feasibility. If  $E \neq \emptyset$ , begin by considering the active player set  $E \in C(N)$ . If so, any weakly efficient LMPE trivially maximizes surplus, as all links are worth zero. Next consider any active player set  $A = E \cup \{i, \eta(i)\}$  for some  $i \in N \setminus E$ . As the LMPE is weakly efficient, there exists a player  $j \in A \setminus E$  such that  $\beta_j(A) > 0$ . But, if so, by taking limits of system (1), we obtain

$$\bar{V}_j(A) = \beta_j(A)(s_{i\eta(i)} - \bar{V}_{\eta(j)}(A)) + (1 - \beta_j(A))\bar{V}_j(A).$$

The latter implies that  $\bar{V}_i(A) + \bar{V}_{\eta(i)}(A) = s_{i\eta(i)}$ . Finally, by induction, assume that any weakly efficient LMPE satisfies  $\bar{V}_i(A) + \bar{V}_{\eta(i)}(A) = s_{i\eta(i)}$  for any  $i \in A \setminus E$  and any  $A \in C(N)$  with cardinality  $|A| \leq |E| + 2k$ . Consider any set  $A \in C(N)$  with cardinality  $|A| = |E| + 2(k + 1)$ . For any player  $i \in A \setminus E$ , defining  $\bar{A}(i) = A_{-i\eta(i)} \setminus E$  and taking limits of system (1) establishes that

$$(\beta_{A \setminus E}(A) - \beta_{\eta(i)}(A))\bar{V}_i(A) = \beta_i(A)(s_{i\eta(i)} - \bar{V}_{\eta(i)}(A)) + \sum_{k \in \bar{A}(i)} \beta_k(A)\bar{V}_i(A_{-k\eta(k)}). \quad (7)$$

By the induction hypothesis, we know that for all  $k \in \bar{A}(i)$ ,

$$\bar{V}_i(A_{-k\eta(k)}) + \bar{V}_{\eta(i)}(A_{-k\eta(k)}) = s_{i\eta(i)}.$$

Exploiting this observation while adding (7) for player  $i$  to that for player  $\eta(i)$  implies that

$$\beta_{A \setminus E}(A)(\bar{V}_i(A) + \bar{V}_{\eta(i)}(A)) = \sum_{k \in A \setminus E} \beta_k(A)s_{i\eta(i)}$$

or, equivalently,  $\bar{V}_i(A) + \bar{V}_{\eta(i)}(A) = s_{i\eta(i)}$ , since by weak efficiency there exists a player  $j \in A \setminus E$  such that  $\beta_j(A) > 0$ . The latter concludes the proof and establishes that any weakly efficient LMPE maximizes surplus.  $\square$

**PROOF OF PROPOSITION 3.** We begin by pinning down strongly efficient MPE payoffs. Consider an MPE strategy in which any player  $i \in N$  offers to his core match  $\eta(i)$  with probability 1 at any active player set  $A \in C(N)$ . If players follow the prescribed strategy, only core matches are ever consummated, and only subgames  $A \in C(N)$  occur on the

equilibrium path. As the core match maximizes the total surplus in an assignment economy, the core match of a player does not change when other core pairs exit the market (that is, it coincides at any subgame  $A \in C(N)$ ). By [Proposition 1](#), we know that any proposer  $i \in A$  necessarily offers an amount equal to  $\delta V_{\eta(i)}(A)$  and that any player  $i \in A$  accepts any offer exceeding  $\delta V_i(A)$ . As players negotiate only with core partners on the equilibrium path, at any  $A \in C(N)$  we guess that

$$V_i(A) = V_i(A_{-j\eta(j)}) \quad \text{whenever } i \in A_{-j\eta(j)}. \quad (8)$$

Thus, at any  $A \in C(N)$ , equilibrium payoffs for every player  $i \in A$  satisfy

$$V_i(A) = p_i(s_{i\eta(i)} - \delta V_{\eta(i)}(A)) + (1 - p_i)\delta V_i(A).$$

Solving the latter equation for player  $i$  with the equation for player  $\eta(i)$  implies that

$$V_i(A) = \frac{p_i}{1 - \delta + \delta p_i} \left( s_{i\eta(i)} - \delta \frac{p_{\eta(i)}}{1 - \delta + \delta p_{\eta(i)}} (s_{i\eta(i)} - \delta V_i(A)) \right),$$

which, after some manipulations, yields

$$V_i(A) = \frac{p_i}{1 - \delta + \delta p_i + \delta p_{\eta(i)}} s_{i\eta(i)},$$

which verifies (8), since value functions are unique for given proposal probabilities by the proof of [Proposition 1](#).

To establish the first part, to the contrary, postulate the existence of a weakly efficient MPE that is not strongly efficient. If so, along any equilibrium path, players either agree with their core partner or delay, which implies that any equilibrium-path subgame is associated to an active players  $A$  set that belongs to  $C(N)$ . Formally, such a requirement amounts to finding a fixed point of the MPE characterization in [Proposition 1](#) that satisfies  $\pi_{ii}(A) + \pi_{i\eta(i)}(A) = 1$  for any  $i \in A$  and any  $A \in C(N)$ . If such an equilibrium were to exist, an argument equivalent to the first part of the proof would imply that for any  $i \in A$  and any  $A \in C(N)$ ,

$$V_i(A) = \frac{p_i \pi_{i\eta(i)}(A)}{1 - \delta + \delta p_i \pi_{i\eta(i)}(A) + \delta p_{\eta(i)} \pi_{\eta(i)i}(A)} s_{i\eta(i)}.$$

But this would give rise to the desired contradiction, as any player  $i$  would strictly prefer immediate agreement with his core match to disagreement, since  $V_i(A)$  strictly increases in  $\pi_{i\eta(i)}(A)$ .  $\square$

**PROOF OF PROPOSITION 4.** First, we establish part (a). Payoffs in any subgame  $A \in C(N)$  of an efficient MPE are pinned down by [Proposition 3](#) for any  $\delta \in (0, 1)$ . We show that complying with efficient strategies yields an equilibrium for any sufficiently high value of  $\delta$ . Recall that any player  $j \in A$  accepts any offer that is worth at least  $\delta V_j(A)$ . Suppose, to the contrary, that some player  $i \in A$  at some subgame  $A \in C(N)$  has a profitable deviation that entails offering to  $j \neq \eta(i)$  when all players comply with strongly

efficient strategies. For such an offer to be profitable for  $i$ , at any sufficiently high  $\delta$ , it must be that

$$s_{ij} - \delta V_j(A) > s_{i\eta(i)} - \delta V_{\eta(i)}(A). \tag{9}$$

However, by taking limits, as  $\delta$  converges to 1, on both sides of this inequality, we obtain

$$s_{ij} - \sigma_j \geq s_{i\eta(i)} - \sigma_{\eta(i)} = \sigma_i.$$

This obviously contradicts the assumption that Rubinstein payoffs are in the interior of the core that requires  $\sigma_i + \sigma_j > s_{ij}$  for all  $i, j \in A$  such that  $j \neq \eta(i)$ . Thus, every player  $i \in A$  at any subgame  $A \in C(N)$  cannot have a profitable deviation when making offers if the discount factor is sufficiently high, which implies the existence of a strongly efficient MPE for any  $\delta$  close to 1.

Next, we establish part (b). To the contrary, assume that a strongly efficient MPE exists for any  $\delta$  close to 1, but that  $\sigma_i + \sigma_j < s_{ij}$  for some pair  $i, j \in N$ . Recall that player  $i$  has a strictly profitable deviation from a strongly efficient equilibrium if condition (9) holds. Since  $\delta V_i \rightarrow \sigma_i$  and  $\delta V_j \rightarrow \sigma_j$ , condition (9) must hold for sufficiently high values of  $\delta$  and player  $i$  must have a profitable deviation for any sufficiently high value of  $\delta$ .  $\square$

**PROOF OF PROPOSITION 5.** To pin down LMPE values, for any player  $i \in N$ , define the outside option partner for player  $i$  as

$$\lambda(i) = \begin{cases} \arg \max_{j \in E} s_{ij} & \text{if } \omega_i > 0, \\ i & \text{if } \omega_i = 0. \end{cases}$$

Therefore,  $\omega_i = s_{i\lambda(i)}$ . An LMPE is strongly efficient if at any active player set  $A \in C(N)$ , all players  $i \notin E$  agree with their core matches  $\eta(i)$  with a probability that converges to 1 (that is,  $\bar{\pi}_{i\eta(i)}(A) = 1$ ) and all players  $i \in E$  delay with a probability that converges to 1 (that is,  $\bar{\pi}_{ii}(A) = 1$ ). Recall that only subgames  $A \in C(N)$  occur on the equilibrium path with positive probability in the limit in a strongly efficient LMPE. Moreover, outside options  $\lambda(i)$  must coincide at every subgame  $A \in C(N)$ , since the core match coincides at any such active player set and since all core unmatched players are active at any such active player set.

To establish that any strongly efficient strategy compatible with equilibrium necessarily yields shifted Rubinstein payoffs as limiting payoffs, we proceed by induction on the size of the active player set within  $C(N)$ , and show that for any  $A \in C(N)$ , any strongly efficient LMPE satisfies

$$\bar{V}_j(A) = \bar{\sigma}_j \quad \text{for any } j \in A. \tag{10}$$

First, consider the smallest active player set in  $C(N)$ , namely,  $A = E$ , when such a set is not empty. If so,  $s_{ij} = 0$  for any  $i, j \in E$ . Obviously,  $V_j(E) = \bar{\sigma}_j = 0$  for any  $j \in E$ . Next, consider any active player set  $A = E \cup \{i, \eta(i)\}$  for some  $i \in N \setminus E$ . Clearly, not both players in  $\{i, \eta(i)\}$  can have binding outside options. If they did, then

$$s_{i\lambda(i)} + s_{\eta(i)\lambda(\eta(i))} \geq s_{i\eta(i)},$$

and an alternative match that generates a weakly higher surplus would be feasible (since both  $\lambda(i)$  and  $\lambda(\eta(i))$  would be unmatched in the core), thereby contradicting the optimality of the core match or its uniqueness. Without loss of generality, if a player has a binding outside option, let that player be  $i$ , so that  $\bar{\sigma}_i = \max\{\omega_i, \sigma_i\}$  and  $\bar{\sigma}_{\eta(i)} = s_{i\eta(i)} - \bar{\sigma}_i$ . Observe that if a player  $j \in E$  plays a strategy converging to efficiency, then for sufficiently high  $\delta$ , he must weakly prefer delaying to offering to a player in  $\{i, \eta(i)\}$ , as  $\bar{\pi}_{jj}(A) = 1$ . If so, then  $v_j(A) = \delta V_j(A)$  and the valuation of such a player necessarily satisfies

$$\bar{V}_j(A) = (1 - p_i - p_{\eta(i)})\bar{V}_j(A) \Rightarrow \bar{V}_j(A) = 0$$

by the characterization in [Proposition 1](#), the definition of strongly efficient LMPEs, and the linearity of the limit operator. Therefore, condition (10) holds for any player  $j \in E$ . Next consider player  $j \in \{i, \eta(i)\}$ . If complying with a strongly efficient strategy is a limiting equilibrium, then for sufficiently high  $\delta$ , it must be that  $v_j(A) = s_{j\eta(j)} - \delta V_{\eta(j)}(A)$ , as  $\bar{\pi}_{j\eta(j)}(A) = 1$ . If so, then for any player  $k \in E$ ,

$$s_{j\eta(j)} - \delta V_{\eta(j)}(A) \geq s_{jk} - \delta V_k(A) = s_{jk},$$

which in turn implies that

$$\bar{V}_j(A) = p_j(s_{j\eta(j)} - \bar{V}_{\eta(j)}(A)) + (1 - p_j)\bar{V}_j(A) \Rightarrow \bar{V}_j(A) \geq s_{jk},$$

establishing that  $\bar{V}_j(A) \geq \omega_j$ . If indeed  $\bar{V}_j(A) > \omega_j$  for any player  $j \in \{i, \eta(i)\}$ , then for any player  $k \in E$  and any  $\delta$  close to 1, we would have that  $\delta V_k(A) + \delta V_j(A) > s_{jk}$ . If so, no player  $k$  would ever agree with  $j$ . If so, the strategy would be strictly efficient for sufficiently high  $\delta$ , and the result would follow by [Proposition 4](#) as

$$\bar{V}_j(A) = \lim_{\delta \rightarrow 1} \frac{p_j}{1 - \delta + \delta p_j + \delta p_{\eta(j)}} s_{j\eta(j)} = \sigma_j > \omega_j.$$

Otherwise, suppose that  $\bar{V}_j(A) = \omega_j$ . If so, taking limits on the characterization in [Proposition 1](#) implies that

$$\bar{V}_{\eta(j)}(A) = p_{\eta(j)}(s_{j\eta(j)} - \bar{V}_j(A)) + (1 - p_{\eta(j)})\bar{V}_{\eta(j)}(A) = s_{j\eta(j)} - \omega_j.$$

The previous observations together imply that  $\bar{V}_k(A) = \bar{\sigma}_k$  for any  $k \in A$ , as  $\bar{V}_i(A) = \bar{\sigma}_i = \max\{\omega_i, \sigma_i\}$  and  $\bar{V}_{\eta(i)}(A) = s_{i\eta(i)} - \bar{\sigma}_i$ .

Next, by induction, assume that  $\bar{V}_j(A) = \bar{\sigma}_j$  for any  $j \in A$  and any active player set  $A \in C(N)$  with cardinality  $|A| = |E| + 2k$ . If so, we show  $\bar{V}_j(A) = \bar{\sigma}_j$  for any  $j \in A$  and any set  $A \in C(N)$  with cardinality  $|A| = |E| + 2(k+1)$ . Consider such a set  $A$ . If a player  $j \in E$  complies with a strongly efficient strategy, then  $v_j(A) = \delta V_j(A)$  for  $\delta$  close to 1, and the valuation necessarily satisfies

$$\begin{aligned} \bar{V}_j(A) &= (1 - p_{A \setminus E})\bar{V}_j(A) + \sum_{k \in A \setminus E} p_k \bar{V}_j(A - k\eta(k)) \\ &= (1 - p_{A \setminus E})\bar{V}_j(A) \Rightarrow \bar{V}_j(A) = 0, \end{aligned}$$

where the first equality follows from the characterization in [Proposition 1](#) and the definition of strongly efficient strategies, while the second equality follows from the induction hypothesis. If a player  $j \in A \setminus E$  complies with a strongly efficient strategy, then  $v_j(A) = s_{j\eta(j)} - \delta V_{\eta(j)}(A)$  for  $\delta$  close to 1. Thus, defining  $\bar{A}(j) = A_{-j\eta(j)} \setminus E$ , the valuation necessarily satisfies

$$\begin{aligned} \bar{V}_j(A) &= (1 - p_{\bar{A}(j)} - p_j)\bar{V}_j(A) + p_j(s_{j\eta(j)} - \bar{V}_{\eta(j)}(A)) + \sum_{k \in \bar{A}(j)} p_k \bar{V}_j(A_{-k\eta(k)}) \\ &= (1 - p_{\bar{A}(j)} - p_j)\bar{V}_j(A) + p_j(s_{j\eta(j)} - \bar{V}_{\eta(j)}(A)) + p_{\bar{A}(j)}\bar{\sigma}_j, \end{aligned}$$

where equalities hold for the same reasons stated above. In this case, the limiting value equations for players  $j$  and  $\eta(j)$  admit a unique solution at

$$\bar{V}_j(A) = \bar{\sigma}_j \quad \text{and} \quad \bar{V}_{\eta(j)}(A) = \bar{\sigma}_{\eta(j)}.$$

To prove the second part of the result, observe that strongly efficient LMPEs mandate play according to the strategies characterized above and payoffs converging to shifted Rubinstein payoffs,

$$\bar{V}_i(A) = \bar{\sigma}_i \quad \text{for any } i \in A \text{ and any } A \in C(N).$$

Toward a contradiction, suppose that agents complied with these strategies, but that  $\bar{\sigma}_i + \bar{\sigma}_j < s_{ij}$  for some pair  $i, j \in N$ . If so, the definition of shifted Rubinstein payoffs would then immediately imply that  $j \notin \{\eta(i), \lambda(i)\}$ . Player  $i$ , however, would then have a profitable deviation when selected to make the first offer in the game. Subgame perfection ensures that  $j$  would accept any offer greater than  $\delta V_j(A)$ . If the player complied with the prescribed strategy by offering to his core partner, his limiting payoff would amount to

$$\lim_{\delta \rightarrow 1} v_i(A) = \bar{\sigma}_i.$$

However, by deviating and offering to  $j$  exactly  $\delta V_j(A)$ , their payoff would increase to

$$\lim_{\delta \rightarrow 1} [s_{ij} - \delta V_j(A)] = s_{ij} - \bar{V}_j(A) = s_{ij} - \bar{\sigma}_j > \bar{\sigma}_i.$$

Thus, for any value of  $\delta$  sufficiently close to 1, player  $i$  would have a strict incentive to deviate and make an acceptable offer to  $j$ . □

**PROOF OF PROPOSITION 6.** In a weakly efficient LMPE,  $\bar{\pi}_{i\eta(i)}(A) + \bar{\pi}_{ii}(A) = 1$  for any player  $i \in A$  for every  $A \in C(N)$ . Thus, all players  $i \in E$  delay with a probability converging to 1 (that is,  $\bar{\pi}_{ii}(A) = 1$ ). In the limit, if all players comply with such strategies, only subgames  $A \in C(N)$  occur on the equilibrium path with positive probability. Recall that the proof of [Proposition 2](#) established that at any active player set  $A \in C(N)$  such that  $A \setminus E \neq \emptyset$  of a weakly efficient LMPE, there exists a player  $i \in A \setminus E$  such that  $\beta_i(A) > 0$  (where  $\beta_i(A) = p_i \bar{\pi}_{i\eta(i)}(A)$ ). To establish that any weakly efficient LMPE that is not strongly efficient must be sequential, we again proceed by induction on the size of

the active player set within  $C(N)$  and we show that there exists  $A \in C(N)$  such that only one core match agrees; that is, for some  $i \in A \setminus E$  such that (3) holds. First, consider the smallest active player set in  $C(N)$ , namely,  $A = E$ , when such a set is not empty. If so, any weakly efficient LMPE is strongly efficient, as the two definitions coincide. Next consider any active player set  $A = E \cup \{i, \eta(i)\}$  for some  $i \in N \setminus E$ . Clearly, there must be agreement on the core match, that is,  $\pi_{i\eta(i)}(A) = \pi_{\eta(i)i}(A) = 1$ , as  $\delta V_i(A) + \delta V_{\eta(i)}(A) < s_{i\eta(i)}$  by feasibility. Thus, any weakly efficient LMPE is strongly efficient.

Next assume by induction that any weakly efficient LMPE is strongly efficient for any active player set  $A \in C(N)$  with cardinality  $|A| = |E| + 2k$ . Consider any set  $A \in C(N)$  with cardinality  $|A| = |E| + 2(k + 1)$ . If a player  $j \in E$  complies with a weakly efficient strategy, then  $v_j(A) = \delta V_j(A)$  for  $\delta$  close to 1. If so, the valuation of  $j$  necessarily satisfies

$$\begin{aligned} \bar{V}_j(A) &= (1 - \beta_{A \setminus E}(A))\bar{V}_j(A) + \sum_{k \in A \setminus E} \beta_k(A)\bar{V}_j(A_{-k\eta(k)}) \\ &= (1 - \beta_{A \setminus E}(A))\bar{V}_j(A) \Rightarrow \bar{V}_j(A) = 0, \end{aligned}$$

where the first equality follows by taking limits of value equations and the definition of weakly efficient strategies, where the second equality follows by the induction hypothesis, and where the implication trivially obtains as  $\beta_{A \setminus E}(A) > 0$  given that at least one core match agrees with positive probability in the limit. If a player  $j \in A \setminus E$  complies with a weakly efficient strategy, then for  $\delta$  close to 1, it must be that  $v_j(A) = \max\{\delta V_j(A), s_{j\eta(j)} - \delta V_{\eta(j)}(A)\}$  by weak efficiency. Taking limits of the value equations for any  $j \in A \setminus E$  while defining  $\bar{A}(j) = A_{-j\eta(j)} \setminus E$  establishes that

$$\begin{aligned} \bar{V}_j(A) &= (1 - \beta_{\bar{A}(j)} - \beta_j)\bar{V}_j(A) + \beta_j(A)[s_{j\eta(j)} - \bar{V}_{\eta(j)}(A)] \\ &\quad + \sum_{k \in \bar{A}(j)} \beta_k(A)\bar{V}_j(A_{-k\eta(k)}) \tag{11} \\ &= (1 - \beta_{\bar{A}(j)} - \beta_j)\bar{V}_j(A) + \beta_j(A)[s_{j\eta(j)} - \bar{V}_{\eta(j)}(A)] + \beta_{\bar{A}(j)}(A)\bar{\sigma}_j, \end{aligned}$$

where the second equality follows by weak efficiency and induction.

If  $\beta_i(A) = 0$  for all players  $i \in \bar{A}(j)$ , then the equilibrium must be sequential by definition.<sup>36</sup> Otherwise, there exists a weakly efficient LMPE in which least two core matches in  $A$  reach agreement with positive probability. If so,  $\beta_i(A) > 0$  and  $\beta_j(A) > 0$  for  $i \neq \eta(j)$ , and thus  $\beta_{\bar{A}(j)} > 0$  for any  $j \in A \setminus E$ . But then the limiting value equations (11) for players  $j$  and  $\eta(j)$  admit a unique solution at

$$\bar{V}_j(A) = \bar{\sigma}_j \quad \text{and} \quad \bar{V}_{\eta(j)}(A) = \bar{\sigma}_{\eta(j)}.$$

The weakly efficient LMPE must be payoff equivalent to a strongly efficient LMPE at  $A$ , thereby fulfilling the induction hypothesis. This establishes that any weakly efficient LMPE that is not strongly efficient must be sequential.

The existence of a sequential LMPE follows by Example 4. □

<sup>36</sup>If so,  $\bar{V}_i(A) = \bar{\sigma}_i$  for all  $i \in \bar{A}(j) \cup E$ , since  $\bar{A}(j) \neq \emptyset$  and  $\bar{V}_i(A \setminus \{k, \eta(k)\}) = \bar{\sigma}_j$  for all  $k \in A \setminus E$  by the induction hypothesis.



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