

Dynamic Kidney Exchange

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We study how barter exchanges should be conducted through a centralized mechanism in a dynamically evolving agent pool with time- and compatibility-based preferences. We derive the dynamically efficient *two-way* and *multi-way* exchange mechanisms that maximize total discounted exchange surplus. Recently several live-donor kidney exchange programmes were established to swap incompatible donors of end-stage kidney disease patients. Since kidney exchange can be modelled as a special instance of our more general model, dynamically efficient kidney exchange mechanisms are derived as corollaries. We make policy recommendations using simulations.

1. INTRODUCTION

There are about 79,000 patients waiting for a kidney transplant in the United States as of March 2009. In 2008, about only 16,500 transplants were conducted, about 10,500 from deceased donors and 6000 from living donors, while about 32,500 new patients joined the deceased donor waiting list and 4200 patients died while waiting for a kidney.¹ Although there is a substantial organ shortage, buying and selling an organ is illegal in many countries in the world, making donation the only source for kidney transplants. Especially in the last decade, the increase in the number of kidney transplants came from the utilization of live donors, who are typically relatives, friends, or spouses of the patients and are willing to donate one of their kidneys. However, many living donors still cannot be utilized, since the potential donor may not be able to donate to her loved one due to blood-type incompatibility or tissue rejection. The medical community has proposed innovative ways to utilize these living donors through *live-donor kidney exchanges* (Rapaport, 1986). In a live-donor kidney exchange, recipients with incompatible donors swap their donors if there is cross-compatibility. Since 1991, kidney exchanges have been done mostly in an *ad-hoc* manner in different countries around the world. Live-donor kidney exchanges accounted for at least 10% of all live donor transplants in Korea and the Netherlands in 2004 (see Park *et al.*, 2004; de Klerk *et al.*, 2005). The medical community has endorsed the practice of live-donor kidney exchanges as ethical (Abecassis *et al.*, 2000). Unlike Korea and the Netherlands, in the United States there is no national system to oversee kidney exchanges as of 2009. Different transplant centres around the country have recently started kidney exchange programmes. For example, New England Program for Kidney Exchange (NEPKE) is an initiative of the transplant centres in New England together with economists (see Roth, Sönmez and Ünver, 2005b), and Alliance for Paired Donation (APD) is an initiative of Dr Michael Rees at University of Toledo and the authors of the above studies. APD has already convinced a large number

1. According to SRTR/OPTN national data retrieved at <http://www.optn.org> on 17 May 2009.

of transplant centres all around the United States to participate. United Network for Organ Sharing is at the stage of launching the national kidney exchange programme in the United States.²

In many of these programmes, a major objective has been to conduct as many transplants as possible. However, one question has frequently arisen in the implementation stage: How often and how exactly should the exchange be run? Roth, Sönmez and Ünver (2004, 2005a) have recently proposed mechanisms to organize kidney exchanges in a Pareto-efficient and dominant strategy incentive-compatible fashion under different constraints on exchange sizes and preferences of the recipients for a static recipient population.

The above studies address the matching aspect of the problem. However, they do not consider the dynamic aspects of the exchange pool evolution.³ From a more general perspective, in the *matching* literature in economics, although there is a significant amount of work on mechanism design in static environments, there is virtually no study on mechanism design for dynamically changing populations, two recent exceptions withstanding.⁴ A recent paper by Bloch and Cantala (2009) analyses house allocation problems in an overlapping generations framework. In their model, they analyse assignment mechanisms that are fair, efficient, and independent. Seniority-based assignment rules characterize these properties when agents are homogeneous. However, when the types of agents are random, efficient and fair rules only exist with two agent types. Independence and efficiency are incompatible in this case. Unlike our model, objects are not attached to agents in their model. Hence, they study assignment rather than exchange. In their model, objects remain in the problem after agents leave the problem. Thus, assignment of an object is not final. Moreover, their general preference structure is not compatibility-based, although they characterize Markovian assignment rules only for a dichotomous model. The second paper related to ours is by Kurino (2008). He studies an overlapping generations model like the Bloch and Cantala paper. However, he does not have random types in his model. Moreover, he introduces property rights. He finds extensions of well-known static mechanisms in the dynamic setting that are individually rational, strategy-proof, and efficient under restrictions of general preferences. Another closely related domain to ours is dynamic allocation setting with changing populations and monetary transfers. For example, Gershkov and Moldovanu (2009a,b) and Said (2009) introduce optimal dynamic mechanisms

2. In Europe, other than the Netherlands, paired kidney exchange programmes have not yet been well organized. The United Kingdom has only recently passed a law that makes kidney exchanges legal. France and Germany have stricter laws, and it is illegal to have a transplant from an unrelated and emotionally distant live donor, making paired exchanges illegal. Spain has an excellent deceased-donor programme. Therefore, live donation is seen as of secondary importance, although there is overwhelming evidence that the long-run survival rates of live-donor organs are far better than deceased-donor organs.

3. In the operations research literature, Zenios (2002) considers a dynamic model with only two types of patient–donor pairs and different outside options. In this model, pairs arrive continuously over time but not in a discrete process like ours. Moreover, since there are only two types of patient–donor pairs and the outside options are different, this model is substantially different from ours. Our model addresses the *matching* aspect of the dynamic kidney exchange problem. On the other hand, Duenyas, Kebliş and Pollock (1997) inspect a specific dynamic matching problem for combining parts of a product produced on an assembly line. In the transplantation context, Su and Zenios (2005) introduce a mechanism design approach for allocating deceased-donor kidneys to patients, when the waiting patients have heterogenous preferences over arriving kidneys and have voluntary participation constraints.

4. There is a vast economics literature on the allocation or exchange of indivisible goods, initiated by Shapley and Scarf (1974); Roth and Postlewaite (1977); Roth (1982); Abdulkadiroğlu and Sönmez (1999); Ergin (2000); Papai (2000); Ehlers (2002); Ehlers, Klaus and Papai (2002); Kesten (2004); Sönmez and Ünver (2005, 2006). None of these works focuses on the stochastic dynamic problem, although Ergin (2000); Ehlers, Klaus and Papai (2002); Sönmez and Ünver (2006) inspect the problem with static exchange rules under varying populations.

when agents arrive over time under Poisson processes in different environments under different objectives.⁵

We consider a general dynamic problem from the point of view of a central authority (e.g. a health authority). Each agent (e.g. a recipient) arrives with an object to trade (e.g. a donor). Waiting in the pool for an exchange is costly. The agent has a need type and objects have object types. The desirability of an object is determined by its type and the need type of the agent. This compatibility relation is a partial order. That is, each agent finds an object with a type that is better than or the same as her own type (other than her own attached object) desirable. Thus, each pair is represented by a pair type determined by the need type of the agent and type of her paired object. Each pair type arrives with a stochastic Poisson arrival process.

The central authority's objective is to minimize the long-run total discounted waiting cost. We make an assumption in the derivation of the efficient *two-way* matching mechanism. We assume that in the long run, there is an arbitrarily large number of *underdemanded* types of pairs, whose object types are not compatible with the needs of recipients' need types. (Later, we show that this assumption is consistent with real-life arrival probabilities of different pairs for the case of kidney exchanges.) We show that an interesting characteristic of an efficient two-way matching mechanism is that it conducts the maximum number of exchanges as soon as they become available; that is, there is no need to sacrifice one or more currently feasible exchanges for the sake of conducting future exchanges (Theorem 1). However, this theorem no longer holds when larger exchanges are feasible, and we derive the efficient multi-way matching mechanism as a *threshold* matching mechanism under one additional assumption (Theorems 2 and 3, also see Remark 1 in Appendix B). In the simplified version of the model, when there are no self-demanded types participating exchange, i.e. types of pairs with the same agent need and object type, a threshold mechanism relies on a single threshold vector. Suppose W_1 and W_2 are two object types that are not comparable under the compatibility partial order; that is, neither W_1 is better than W_2 , nor W_2 is better than W_1 . Then, the efficient mechanism considers the number of W_1 - W_2 type pairs (W_1 type agents and W_2 type paired-objects) and reciprocal W_2 - W_1 type pairs together. Depending on the frequencies of arrival of different pairs, one of the two types of threshold mechanisms is efficient. In the first possible solution, the efficient mechanism conducts the maximum size exchanges as soon as they become available as long as there are no W_2 - W_1 type pairs. However, if there are some W_2 - W_1 type pairs already available in the exchange pool, and their number does not exceed a threshold number, then the authority should not use the W_2 - W_1 type pairs other than matching W_1 - W_2 type pairs. In this case, it should avoid involving them in larger exchanges that do not have W_1 - W_2 type pairs. Only when the stock of W_2 - W_1 type pairs exceeds the threshold number should the authority conduct the largest possible exchanges as soon as they become available, and possibly use W_2 - W_1 type pairs in exchanges without W_1 - W_2 type of pairs. The second possible solution is just the symmetric version of the first solution, and instead treats W_1 - W_2 type pairs as the stock variable. The mechanism takes into account all such non-comparable W_1 and W_2 types. We show that decisions regarding each incomparable object type W_1 and W_2 are independent from those regarding other incomparable object types (Propositions 2 and 6).

5. A recent paper by Abdulkadiroğlu and Loertscher (2006) inspects the dynamic preference formation in house allocation problems. In other domains, there are several recent studies on optimal mechanisms in dynamic settings. For example, Jackson and Palfrey (1998) study optimal bargaining mechanisms in a dynamic setting, and Skreta (2006) studies optimal dynamic mechanism design when the designer cannot commit to a mechanism in the future. Another topic that is attracting recent attention is optimal auction design when valuation signals of agents evolve over time (e.g. Bergemann and Välimäki, 2006; Athey and Segal, 2007).

Our constraints in the general model are consistent with the medical and institutional constraints of the kidney exchange problem.

First, in the medical literature, Gjertson and Cecka (2000) and Delmonico (2004) pointed out that a recipient is indifferent between two live-donor kidneys as long as they are both compatible with the recipient. We adopt this assumption in our current study and assume that the preferences of the recipients fall into three indifference classes: being matched to a compatible kidney, being unmatched, and being matched to an incompatible kidney.⁶ We also introduce time preferences of recipients into the dynamic setting. This is consistent with our general model's assumptions.

Second, the practice of kidney exchange has started by conducting exchanges that include only two recipients and their incompatible donors. More complicated exchanges that include three or more recipients (and their donors) will take place less frequently, because all transplants of a single exchange cycle should take place simultaneously. Otherwise, some donors could potentially back out after their recipients receive transplants given the legal constraint that it is illegal to force a donor to sign a contract that would commit him to donation. Nevertheless, Roth, Sönmez and Ünver (2007) have shown that larger exchanges, especially three-way exchanges including three recipient–donor pairs, would substantially increase the gains from exchange. In the current paper, we separately derive efficient dynamic matching mechanisms that conduct *two-way exchanges* and *multi-way exchanges*, which is consistent with our general derivation.

Since blood-type compatibility needed for kidney donations is a special case of the above compatibility partial order, the efficient kidney exchange mechanism is a special instance of the general mechanism under certain assumptions. We compute the efficient mechanism under different pair arrival rates and time discount rates. Additionally, we conduct policy simulations and observe that the gains under the efficient multi-way kidney exchange mechanism are significantly higher than those under the efficient two-way mechanism.

2. THE GENERAL DYNAMIC EXCHANGE MODEL

2.1. Exchange pool

We consider an exchange model in which each agent arrives at the exchange pool with an (indivisible) object to trade through barter exchange. A pair i consists of an agent a_i and her object o_i . There is a requirement type for each agent over the objects and each object belongs to one of these types. Let \mathcal{T} be the finite set of requirement/object types. Since each agent's requirement and each object belongs to one of these types, there are $|\mathcal{T}|^2$ permutations for each pair. We call each of these permutations a *pair type*. The type of a pair is denoted as $X-Y$ where $X, Y \in \mathcal{T}$ and X is the requirement type of the agent and Y is the type of her object. Let $\mathcal{P} = \mathcal{T} \times \mathcal{T}$ be the set of pair types. For any pair type $X-Y \in \mathcal{P}$, let p_{X-Y} be the probability of a random pair being of type $X-Y$. We refer to p_{X-Y} as the *arrival probability* of pair type $X-Y \in \mathcal{P}$. We have $\sum_{X-Y \in \mathcal{P}} p_{X-Y} = 1$. For any $X-Y \in \mathcal{P}$, we refer to $Y-X$ as the *reciprocal pair type* of $X-Y$.

We define a universal binary relation \blacktriangleright over \mathcal{T} as follows: for any $X, Y \in \mathcal{T}$, $X \blacktriangleright Y$ means that an object of type X can be consumed by an agent of requirement type Y , and we refer to this as *X is compatible with Y*.

We make some restrictions on the compatibility relation \blacktriangleright . We assume that \blacktriangleright is a *partial order*, i.e. it is reflexive, transitive, and antisymmetric.

6. We have the same assumption in Roth, Sönmez and Ünver (2005a, 2007).

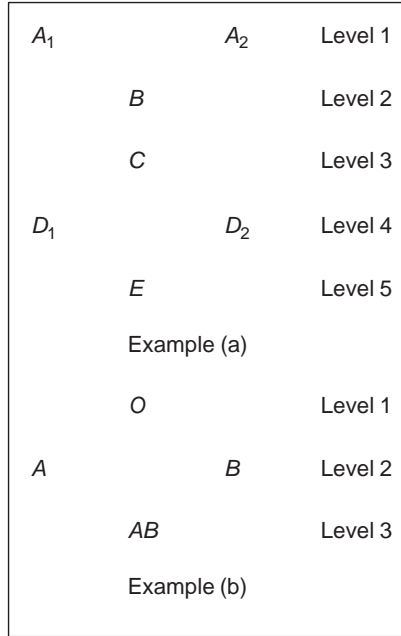


FIGURE 1

Example (a) $\mathcal{T} = \{A_1, A_2, B, C, D_1, D_2, E\}$ such that $A_1, A_2 \blacktriangleright B \blacktriangleright C \blacktriangleright D_1, D_2 \blacktriangleright E$; $A_1 \blacktriangleright A_2$; $A_2 \blacktriangleright A_1$; $D_1 \blacktriangleright D_2$; and $D_2 \blacktriangleright D_1$. **Example (b)** In kidney exchange, $\mathcal{T} = \{O, A, B, AB\}$ is the set of blood types of recipients and donors such that kidney compatibility relation \blacktriangleright satisfies $O \blacktriangleright A, B \blacktriangleright AB$; $A \blacktriangleright B$; $B \blacktriangleright A$

Though \blacktriangleright is not a complete relation (i.e. not a linear order), for simplicity, we assume that for any type $X \in \mathcal{T}$, there exists at most one type in $Y \in \mathcal{T}$ that is not comparable with X . That is, for any $X \in \mathcal{T}$, there exists at most one $Y \in \mathcal{T}$ such that neither $X \blacktriangleright Y$ nor $Y \blacktriangleright X$ is true.⁷

Based on the compatibility relation, we can partially order types in levels. Let the level set $\mathcal{L} = \{1, 2, \dots, |\mathcal{L}|\}$ be the partition of \mathcal{T} such that for all $K, L \in \{1, 2, \dots, |\mathcal{L}| - 1\}$ with $K < L$, if $X \in K$ and $Y \in L$, then $X \blacktriangleright Y$. In this case, we say that X is at a better compatibility level than Y . Observe that for any $L \in \mathcal{L}$, $X, Y \in L$ with $X \neq Y$ imply $X \blacktriangleright Y$ and $Y \blacktriangleright X$. For each compatibility type $X \in \mathcal{T}$, let $L_X \in \mathcal{L}$ be the compatibility level of X , i.e. $X \in L_X$. Though both notations, levels, and binary relation \blacktriangleright , can be used interchangeably, we will stick to the latter in most parts of the paper. We will use levels to quantify the magnitude of difference between levels of different types. See Figure 1 for two examples of feasible type sets and compatibility partial orders.

An agent cannot consume her own object. Each agent would like to consume another pair’s object that is compatible with her. We assume that pairs arrive over time with a stochastic (discrete) Poisson arrival process in continuous time. Let λ be the arrival rate of the pairs, i.e. the expected number of pairs that arrive per unit time. Thus, each type X – Y arrives with a Poisson arrival process with rate $p_{X-Y}\lambda$. The *exchange pool* is the set of the pairs that arrived over time whose agent has not yet been assigned an object.

Each agent has preferences over objects and over time of waiting in the pool. Compatible objects are preferred to being unmatched. In turn, being unmatched is preferred to being

7. This assumption is the minimal structure needed to generate a result as in our Theorem 2.

matched to incompatible objects.⁸ Moreover, time spent in the exchange pool is another dimension in the preferences of agents: waiting is costly. We will model the waiting cost through a fixed cost.

2.2. Exchange

An *exchange* is a list of pairs (i_1, i_2, \dots, i_k) for some $k \geq 2$ such that for any $\ell < k$, object o_{i_ℓ} is assigned to agent $a_{i_{\ell+1}}$, and object o_{i_k} is assigned to agent a_{i_1} . We will sometimes refer to an exchange by the types of the participating pairs, i.e. as $(A_1-O_1, \dots, A_k-O_k)$ where $A_\ell-O_\ell$ is the pair type of i_ℓ . A *matching* is a set of exchanges such that each pair participates in at most one exchange. A matching or an exchange is *individually rational* if it never matches an agent with an incompatible object. From now on, when we talk about an exchange or a matching, it will be individually rational. A matching is *maximal* if it matches the maximum number of pairs possible at an instance of the pool.

A *(dynamic) matching mechanism* is a dynamic procedure such that at each time $t \geq 0$ it selects a (possibly empty) matching of the pairs available in the pool. Once a pair is matched at time t by a matching mechanism, it leaves the pool and its agent receives the assigned object.

Let $A(t)$ represent the set of pairs that arrived at the pool until time t . If a matching mechanism ϕ is executed (starting time 0), $\phi(t, A)$ is the set of pairs matched by mechanism ϕ under the flow A . There are $|A(t)| - |\phi(t, A)|$ pairs available at the pool at time t .

2.3. Dynamically efficient mechanisms

There is a central authority that oversees the exchanges. For each pair, we associate waiting in the pool with a monetary cost and we assume that there is a constant *unit time cost* $c > 0$ of waiting for an exchange.⁹

Suppose that the central authority implements a matching mechanism ϕ . For any time t , the current value of expected cost at time t under matching mechanism ϕ is given as¹⁰

$$E_t [C^\phi(t, A)] = \int_t^\infty c E_t [|A(\tau)| - |\phi(\tau, A)|] e^{-\rho(\tau-t)} d\tau, \tag{1}$$

where ρ is the *discount rate*.

For any time τ, t such that $\tau > t$, we have $E_t [|A(\tau)|] = \lambda(\tau - t) + |A(t)|$, where the first term is the expected number of pairs to arrive at the exchange pool in the interval $[t, \tau]$ and the second term is the number of pairs that arrived at the pool until time t . Therefore, we can rewrite $E_t [C^\phi(t, A)]$ as

$$E_t [C^\phi(t, A)] = \int_t^\infty c (\lambda(\tau - t) + |A(t)| - E_t [|\phi(\tau, A)|]) e^{-\rho(\tau-t)} d\tau.$$

8. In the context of kidney transplantation, Gjertson and Cecka (2000) point out that each compatible live-donor kidney will last approximately the same amount of time as long as the donor is not too old and in relatively in good health.

9. In the context of kidney exchanges, the alternative option of a transplant is dialysis. A patient can undergo dialysis continuously. It is well known that receiving a transplant causes the patient to resume a better life (cf. Overbeck *et al.*, 2005). Also healthcare costs for dialysis are more than those for transplantation in the long term (cf. Schweitzer *et al.*, 1998). We model all the costs associated with undergoing continuous dialysis by the unit time cost c .

10. E_t refers to the expected value at time t .

Since $\int_t^\infty e^{-\rho(\tau-t)} d\tau = \frac{1}{\rho}$ and $\int_t^\infty (\tau - t) e^{-\rho(\tau-t)} d\tau = \frac{1}{\rho^2}$, we can rewrite $E_t [\mathcal{C}^\phi(t, A)]$ as

$$E_t [\mathcal{C}^\phi(t, A)] = \frac{c\lambda}{\rho^2} + \frac{|A(t)|}{\rho} - \int_t^\infty c E_t [|\phi(\tau, A)|] e^{-\rho(\tau-t)} d\tau. \tag{2}$$

Only the last term in equation (2) depends on the choice of mechanism ϕ . The previous terms cannot be controlled by the central authority, since they are the costs associated with the number of pairs arriving at the pool. We refer to this last term as the *exchange surplus at time t for mechanism ϕ* and denote it by

$$\mathcal{ES}^\phi(t, A) = \int_t^\infty c E_t [|\phi(\tau, A)|] e^{-\rho(\tau-t)} d\tau. \tag{3}$$

We can rewrite it as

$$\begin{aligned} \mathcal{ES}^\phi(t, A) &= \int_t^\infty c (E_t [|\phi(\tau, A)| - |\phi(t, A)|] + |\phi(t, A)|) e^{-\rho(\tau-t)} d\tau \\ &= \frac{c |\phi(t, A)|}{\rho} + \int_t^\infty c (E_t [|\phi(\tau, A)| - |\phi(t, A)|]) e^{-\rho(\tau-t)} d\tau. \end{aligned} \tag{4}$$

The first term above is the exchange surplus attributable to all exchanges that have been done until time t and at time t , and the second term is the *future exchange surplus* attributable to the exchanges to be done in the future. The central authority cannot control the number of past exchanges at time t either. Let $n^\phi(\tau, A)$ be the *number of matched recipients at time τ by mechanism ϕ* , and we have¹¹

$$|\phi(t, A)| = \left(\sum_{\tau < t} n^\phi(\tau, A) \right) + n^\phi(t, A). \tag{5}$$

We focus on the *present and future exchange surplus*, which is given as

$$\widetilde{\mathcal{ES}}^\phi(t) = \frac{cn^\phi(t, A)}{\rho} + \int_{t^+}^\infty c (E_t [|\phi(\tau, A)| - |\phi(t, A)|]) e^{-\rho(\tau-t)} d\tau. \tag{6}$$

A dynamic matching mechanism ϕ is *efficient* if for any t , it maximizes the *present and future exchange surplus* at time t given in equation (6). We look for solutions of the problem independent of initial conditions and time t .¹²

3. DYNAMICALLY EFFICIENT TWO-WAY MATCHING MECHANISMS

In this section, we derive the dynamically efficient *two-way* matching mechanism. A *two-way exchange* is an exchange involving only two pairs. A matching is a *two-way matching* if all exchanges in the matching are two-way exchanges. It will be useful to introduce the following concepts about two-way exchanges. We say that two pairs i and j are *mutually compatible* if object o_i is compatible with agent a_j and object o_j is compatible with agent a_i .

11. For each finite time t , since with probability 1 the arrival interval between each arrival is finite and bounded from below, almost surely the total arrivals will be a finite number. However, at the limit $t = \infty$, this may not be correct. Thus, we will use a steady-state representation to handle the limit case.

12. We will define a steady-state formally. If such solutions exist, they depend only on the “current state of the pool” (defined appropriately) but not on time t or the initial conditions.

The following observation states the important individual rationality constraints that need to be respected in our derivation of an efficient matching mechanism:

Observation 1. *A pair of type $X-Y$ can participate in a two-way exchange only with a mutually compatible pair, i.e. a pair of type $W-Z$ such that $Y \blacktriangleright W$ and $Z \blacktriangleright X$.*

We partition the set of pair types into four sets \mathcal{P}^O , \mathcal{P}^U , \mathcal{P}^S , and \mathcal{P}^R as follows:
We refer to the set

$$\mathcal{P}^O = \{X-Y \in \mathcal{P} : Y \blacktriangleright X \text{ and } X \neq Y\} \tag{7}$$

as the set of *overdemanded* pair types. Since $Y \blacktriangleright X$, in two-way exchanges these pairs can save pairs of other $W-Z$ types with $Y \blacktriangleright W$ and $Z \blacktriangleright X$. These $W-Z$ types can satisfy (a) $W \blacktriangleright Z$ with $W \neq Z$, (b) $W \blacktriangleright Z$ and $Z \blacktriangleright W$, (c) $W = Z$, and (d) $Z \blacktriangleright W$ with $W \neq Z$. Class (d) $W-Z$ types are also included in \mathcal{P}^O . We will create other sets for $W-Z$ types in classes (a), (b), and (c) as follows:

We refer to the set

$$\mathcal{P}^U = \{X-Y \in \mathcal{P} : X \blacktriangleright Y \text{ and } X \neq Y\} \tag{8}$$

as the set of *underdemanded* pair types $X-Y$, which can participate in two-way exchanges with pair types $W-Z$ with $Y \blacktriangleright W$ and $Z \blacktriangleright X$. Since $W \blacktriangleright Z$ and $W \neq Z$, by transitivity $Y \blacktriangleright X$ and $X \neq Y$. Hence, underdemanded types can only be matched with certain overdemanded pair types.

We refer to the set

$$\mathcal{P}^S = \{X-X \in \mathcal{P}\} \tag{9}$$

as the set of *self-demanded* pair types. Self-demanded types $X-X$ can only be matched with $X-X$ type pairs or types $W-Z$ with $Z \blacktriangleright X \blacktriangleright W$ and $Z \neq W$, which are certain overdemanded pairs.

We refer to the set

$$\mathcal{P}^R = \{X-Y \in \mathcal{P} : X \blacktriangleright Y \text{ and } Y \blacktriangleright X\} \tag{10}$$

as the set of *reciprocally demanded* types. They can only be matched with their reciprocal types $Y-X$ and certain pairs $W-Z$ with $Z \blacktriangleright X$, $Y \blacktriangleright W$ and $Z \neq W$, which are certain overdemanded pairs.¹³

Throughout this section we will maintain one assumption:

Assumption 1 (Long-run assumption). *Under any dynamic matching mechanism, in the long run, there is an arbitrarily large number of underdemanded pairs from each pair type in the exchange pool.*¹⁴

13. We will typically use the notations $X-Y$, Z_1-Z_2 , $V-V$, and W_1-W_2 to denote a generic *overdemanded*, *underdemanded*, *self-demanded*, and *reciprocally demanded* pair type, respectively. When it is not ambiguous, we will use $X-Y$ and $W-Z$ also to denote generic pair types.

14. When we discuss the example of kidney exchanges, we will show that regardless of the two-way matching mechanism used, this assumption will hold under realistic arrival probabilities for the pairs in our application for kidney exchange.

Since we are interested in maximizing the exchange surplus and cannot control the inflow of the pairs, this assumption will not harm our objective, even though under cost minimization this assumption leads to ∞ cost for any matching mechanism.

We state the following Lemma directly using the construction of sets \mathcal{P}^O , \mathcal{P}^U , \mathcal{P}^S , \mathcal{P}^R and their properties stated above (we skip its proof for brevity):

Lemma 1. *In a static population of pairs under Assumption 1, where n_{x-y} denotes the number of pairs of any type $X-Y \in \mathcal{P}$, the maximum number of pairs matched through two-way exchanges is given by¹⁵*

$$\sum_{X-Y \in \mathcal{P}^O} 2n_{x-y} + \sum_{V-V \in \mathcal{P}^S} \left\lfloor \frac{n_{v-v}}{2} \right\rfloor + \sum_{W_1-W_2 \in \mathcal{P}^R} \min \{n_{w_1-w_2}, n_{w_2-w_1}\}.$$

We are ready to state our main result of this section:

Theorem 1. *Let dynamic matching mechanism ν be such that it matches only $X-Y$ type pairs with their reciprocal $Y-X$ type pairs immediately when such an exchange is feasible. Then, under Assumption 1,*

- *mechanism ν is a dynamically efficient two-way matching mechanism; and*
- *any dynamically efficient two-way matching mechanism conducts a two-way exchange whenever one becomes feasible.*

Let dynamic two-way matching mechanism ν be defined as in the hypothesis of Theorem 1, that is, for any arriving pair of any type $X-Y \in \mathcal{P}$, mechanism ν matches this pair immediately with an existing $Y-X$ type pair if such a mutually compatible pair exists in the pool, and does not perform any exchanges, otherwise.

We will prove Theorem 1 using the following proposition:

Proposition 1. *Under Assumption 1, within any time interval τ , mechanism ν matches the maximum number of pairs possible under any two-way matching mechanism.*

Proof of Proposition 1. Suppose that Assumption 1 holds. Suppose that mechanism ν is used for the exchange. Consider a time interval $\tau > 0$ in the long run. Let t_0 be the start of this time interval and $t_1 = t_0 + \tau$ be the end of this time interval. Since each type is matched with its reciprocal type under mechanism ν , in the long run we have,

- (1) for any type $Z_1-Z_2 \in \mathcal{P}^U$, by Assumption 1, there will be an arbitrarily large number of type Z_1-Z_2 pairs available;
- (2) for any type $X-Y \in \mathcal{P}^O$, since there is an arbitrarily large number of type $Y-X$ pairs available (by Statement 1 above), for any incoming $X-Y$ type pair i there will exist at least one $Y-X$ type pair that is mutually compatible, and mechanism ν will immediately match these two pairs, implying that no type $X-Y$ pairs will remain available;
- (3) for any type $V-V \in \mathcal{P}^S$, whenever x type $V-V$ pairs are available in the exchange pool, mechanism ν will match $2\lfloor \frac{x}{2} \rfloor$ of these pairs with each other, implying that there will be 0 or 1 type $V-V$ pair available;
- (4) for any $W_1-W_2 \in \mathcal{P}^R$, there is either no W_2-W_1 pair in the pool or there are finitely many. If there is a W_2-W_1 type pair, this pair and the incoming pair are mutually compatible

15. For any real number x , $\lfloor x \rfloor$ represents the greatest integer less than or equal to x .

and mechanism ν will immediately match these two pairs. In the pool, there will be either (1) no W_1-W_2 type pair and no W_2-W_1 type pair remaining, (2) no W_2-W_1 type pair and some W_1-W_2 type pairs remaining, or (3) no W_1-W_2 type pair and some W_2-W_1 type pairs remaining.

Clearly, the maximum number of exchanges in the interval $[t_0, t_1]$ is performed by not conducting any exchanges in interval $[t_0, t_1)$ and then conducting the maximal exchange at time t_1 . Since time interval τ is finite, Statement 1 above is still valid at any time $t \in [t_0, t_1]$, regardless of which exchanges are conducted in $[t_0, t_1)$. Therefore, by Lemma 1, the maximum number of transplants that can be conducted in interval $[t_0, t_1]$ is

$$\sum_{X-Y \in \mathcal{P}^O} 2n_{X-Y} + \sum_{V-V \in \mathcal{P}^S} \left\lfloor \frac{n_{V-V}}{2} \right\rfloor + \sum_{W_1-W_2 \in \mathcal{P}^R} \min \{n_{W_1-W_2}, n_{W_2-W_1}\} \tag{11}$$

where n_{X-Y} is the number of type $X-Y$ pairs that are available at time t_1 , if no exchange has been conducted in interval $[t_0, t_1)$. Moreover, for any $X-Y \in \mathcal{P}$, this number in equation (11) can be achieved by matching each $X-Y$ type pair with a reciprocal type pair, as long as it is possible.

Next consider the scenario in which mechanism ν is used in interval $[t_0, t_1)$. Statements 1–4 above are valid for any time $t \in [t_0, t_1)$ under mechanism ν . Therefore, under mechanism ν , the number of matched pairs in interval $[t_0, t_1]$ is

- $\sum_{X-Y \in \mathcal{P}^O} 2n_{X-Y}$ for the overdemanded and underdemanded pairs by Statements 1 and 2,
- $\sum_{V-V \in \mathcal{P}^S} \lfloor \frac{n_{V-V}}{2} \rfloor$ for the self-demanded types by Statement 3, and
- $\sum_{W_1-W_2 \in \mathcal{P}^R} \min \{n_{W_1-W_2}, n_{W_2-W_1}\}$ for the reciprocally demanded types by Statement 4,

and their sum is exactly equal to the expression given in equation (11), completing the proof of Proposition 1. \parallel

Theorem 1 can be proven using Proposition 1.

Proof of Theorem 1. Suppose that Assumption 1 holds. Fix time τ in the long run. For any mechanism ϕ and any time $t > \tau$, $|\phi(t, A)| - |\phi(\tau, A)|$ is the total number of recipients matched between time τ and t under mechanism ϕ when the flow function is given by A , and is maximized by the mechanism ν by Proposition 1. Since $|\phi(t, A)| - |\phi(\tau, A)|$ is *ex-post* maximized for $\phi = \nu$ for any $t \geq \tau$, $E_\tau [|\phi(t, A)| - |\phi(\tau, A)|]$ is maximized by $\phi = \nu$, as well. Moreover, mechanism ν conducts the maximum possible number of exchanges at any given point in time as 0 or 2 (permitted by the two-way exchange restriction). Therefore, $n^\phi(\tau, A)$ is also maximized by $\phi = \nu$. These imply $\mathcal{ES}^{*\phi}(\tau) = \frac{cn^\phi(\tau, A)}{\rho} + \int_\tau^\infty cE_\tau [|\phi(t, A)| - |\phi(\tau, A)|] e^{-\rho(t-\tau)} dt$ is maximized for $\phi = \nu$, implying that ν is an efficient two-way matching mechanism. Moreover, it conducts the maximum number of transplants at each time, completing the proof of Theorem 1. \parallel

Note that since we can roughly define an efficient mechanism ν independent of the state of the pool, we did not introduce an explicit state space for the pool. It turns out that under multi-way exchanges, an efficient mechanism explicitly depends on the state.

4. DYNAMICALLY EFFICIENT MULTI-WAY MATCHING MECHANISMS

In this section, we consider matching mechanisms that allow not only two-way exchanges, but larger exchanges as well. We maintain Assumption 1 throughout this section. Hence, there are arbitrarily many underdemanded pairs in the exchange pool in the long run.

We state Proposition 2 as follows:

Proposition 2 (Necessary and sufficient conditions for matching underdemanded, self-demanded, and reciprocally demanded types in multi-way exchanges). *Suppose that there exists exactly one overdemanded pair in the exchange pool, and it is of some type $X-Y \in \mathcal{P}^O$. Then:*

- *An underdemanded pair of type $Z_1-Z_2 \in \mathcal{P}^U$ can be matched in a multi-way exchange if and only if $X \blacktriangleright Z_2$ and $Z_1 \blacktriangleright Y$ and we use the overdemanded pair; if $Y \blacktriangleright Z_1$, then we use an additional reciprocally demanded pair of type $Y-Z_1 \in \mathcal{P}^R$; and if $Z_2 \blacktriangleright X$, then we use an additional reciprocally demanded pair of type $Z_2-X \in \mathcal{P}^R$.*
- *A self-demanded pair of type $V-V \in \mathcal{P}^S$ can be matched in a multi-way exchange if and only if*
 - *we use another pair of type $V-V$,*
 - or*
 - *$X \blacktriangleright V$ and $V \blacktriangleright Y$ and we use the overdemanded pair; if $Y \blacktriangleright V$, then we use an additional reciprocally demanded pair of type $Y-V \in \mathcal{P}^R$; and if $V \blacktriangleright X$, then we use an additional reciprocally demanded pair of type $V-X \in \mathcal{P}^R$.*
- *A reciprocally demanded pair of type $W_1-W_2 \in \mathcal{P}^R$ can be matched in a multi-way exchange if and only if*
 - *we use a reciprocal W_2-W_1 type pair,*
 - or*
 - *$Y \blacktriangleright Z_1$ and $Z_2 \blacktriangleright X$ and we use the overdemanded pair of type $X-Y$.*

The proof of the above proposition is in Appendix A. We also state and prove Proposition 6, which is in regard to the sizes of maximal exchanges in Appendix A. These two propositions bring several simplifications to the optimization problem.

Suppose that $X-Y \in \mathcal{P}^O$ is the pair type of an arriving overdemanded pair, i.e. $Y \blacktriangleright X$ and yet $Y \neq X$. Instead of matching this pair and serving one underdemanded pair (as in two-way exchanges, for example, by matching it with a pair of type $Y-X$), we can potentially use this pair in larger exchanges to serve more underdemanded pairs, if multi-way exchanges are allowed.

It could also be the case that there are multiple reciprocally demanded pairs of different compatibility levels existent in the exchange pool when the $X-Y$ type overdemanded pair arrives. Without loss of generality, we can assume that no two of these types are at the same compatibility level. If they were, we could have matched the pairs of these types with each other in two-way exchanges until one of them has no more pairs left. It could also be the case that there are multiple self-demanded pairs at different compatibility levels in the exchange pool. Without loss of generality, we can assume that no two of these pairs have the same pair type (since otherwise, if there are $k > 1$ pairs of type $V-V$, we could serve them in a k -way exchange as $V-V, V-V, \dots, V-V$).

We will refer to the pairs satisfying the conditions in Proposition 2 to be matched using an overdemanded pair as *matchable* pairs. We state the following corollary to Proposition 6 about matchable pairs:

Corollary 1. *Under Assumption 1, when there is a single overdemanded type pair of type $X-Y$, under an efficient mechanism,*

- *we match L_X-L_Y underdemanded pairs; and*

- *decisions regarding matchable self-demanded and reciprocally demanded pairs with object and agent types located at different compatibility levels of the partial order ► are independent from each other.*

That is, under an efficient mechanism, not only can we match the maximum number of possible underdemanded pairs, but we can always enlarge an exchange by squeezing in a matchable reciprocally demanded or self-demanded pair belonging to a different compatibility level than the ones in the exchange, at the cost of replacing only underdemanded pairs in the exchange with different ones. Suppose an exchange E has been fixed with a single overdemanded pair. Then we can squeeze in a reciprocally demanded pair (if the conditions in Proposition 2 are satisfied) without affecting the rest of the overdemanded, reciprocally demanded, and self-demanded pairs in E , and match the same number of underdemanded pairs as E does. We can almost do the same thing using a self-demanded pair except if there is already another self-demanded pair of a compatibility type that is incomparable to this pair. In the latter case, a new reciprocally demanded pair belonging to this compatibility level is also needed (see Footnote 32). The new exchange may replace at most two underdemanded pairs of E with new ones. Since by Assumption 1 underdemanded pairs are abundant, this minimal change will have no effect on optimization. An example of such insertions is given below using the type sets in Figure 1(a).

An example regarding overdemanded type pairs helping out other pairs in multi-way exchanges: Consider the types in Figure 1(a). Suppose that an $E-A_1$ type overdemanded pair arrives under Assumption 1. $E-A_1$ can be used to match all underdemanded, self-demanded, and reciprocally demanded pairs. Figure 2 shows a number of exchanges that can be conducted through the $E-A_1$ type pair. Exchange (a) is conducted to match the maximum number of underdemanded pairs, which is $L_{A_1} - L_E = 4$. In Exchange (b), we *squeeze in* an A_1-A_2 type reciprocally demanded pair by replacing pair 3 in Exchange (a) with pair 7. In Exchange (c), we additionally *squeeze in* a D_2-D_2 type self-demanded pair by replacing pairs 4 and 5 in Exchange (b) with pairs 8 and 10, respectively. In Exchange (d), we *squeeze in* a D_1-D_1 type self-demanded pair. However, there is already another pair at the same compatibility level, namely pair 9 of type D_2-D_2 . Thus, we need an additional D_1-D_2 or D_2-D_1 type reciprocally demanded pair to accommodate this new pair together with pair 9. In the figure, we use pair 12 of type D_1-D_2 as a “bridge pair” between D_1-D_1 and D_2-D_2 type pairs. In this case, we also replace underdemanded pair 8 with pair 4.

All the above results assume that there exists at most one overdemanded pair in the pool. However, if we do not match an overdemanded pair immediately, there can be more than one. We state one other assumption, which will ensure that an overdemanded pair will never be kept in the pool.

Suppose that W_1-W_2 and W_2-W_1 are two reciprocally demanded pair types at the same compatibility level. We show that as long as the difference between W_1-W_2 and W_2-W_1 type arrival frequencies is not large, overdemanded type pairs will be matched immediately under the efficient mechanism. The proof of this proposition is given in Appendix A.

Proposition 3. *Suppose Assumption 1 holds. If for all W_1-W_2 and $W_2-W_1 \in \mathcal{P}^R$, $p_{W_1-W_2}$ and $p_{W_2-W_1}$ are sufficiently close to each other, then under any dynamically efficient multi-way matching mechanism, overdemanded type pairs are matched as soon as they arrive at the exchange pool.*

We state the hypothesis of this proposition as an assumption.

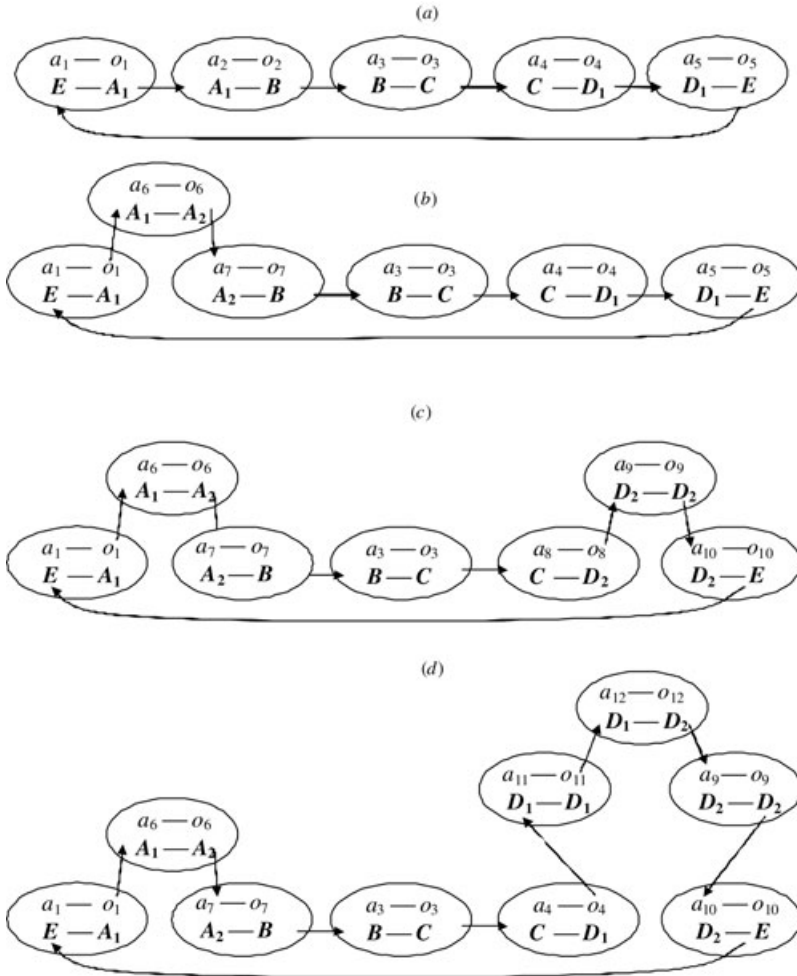


FIGURE 2
 Examples of multi-way exchanges that can be conducted through an E-A₁ type overdemanded pair for the pair types given in Figure 1(a)

Assumption 2 (Assumption on generic arrival rates of reciprocally demanded types). For all $W_1 - W_2$ and $W_2 - W_1 \in \mathcal{P}^R$, $p_{W_1 - W_2}$ and $p_{W_2 - W_1}$ are sufficiently close to each other so that all overdemanded pairs are matched immediately under an efficient mechanism.

Under Assumptions 1 and 2, since an overdemanded pair will be matched immediately when it arrives, we will only need to make decisions in situations in which multiple exchanges of different sizes are feasible. Thus, using multi-way exchanges, we can benefit from not conducting the largest feasible exchange currently available and holding onto some of the pairs, which can currently participate in an exchange, in the expectation of saving more pairs sooner.

For example, consider a situation in which an overdemanded X-Y type pair arrives at the pool, while a reciprocally demanded $W_1 - W_2$ type pair which can be matched using the X-Y type pair is also available.

By Corollary 1, the decisions regarding the W_1-W_2 type pair are independent from decisions regarding other reciprocally demanded pair types except type W_2-W_1 .¹⁶ Since by Assumption 1 there is an excess number of underdemanded type pairs in the long run, by Corollary 1 there are two candidates for an optimal exchange: for some number n

- an n -way kidney exchange without the W_1-W_2 type pair or
- an $(n + 1)$ -way exchange including the W_1-W_2 type pair.¹⁷

Which exchange should the central authority choose?

We answer this question by converting the problem to an embedded *Markov decision process* with a state space consisting of $|\mathcal{P}|$ dimensional integer vectors that show the number of pairs in the pool belonging to each pair-type.^{18,19} There is additional structure to eliminate some of these state variables under Assumptions 1 and 2:

- *For the overdemanded types:* If an overdemanded pair i of type $X-Y \in \mathcal{P}^O$ arrives, by Proposition 3, pair i will be matched immediately in some exchange. Hence, the number of overdemanded pairs remaining in the pool is always 0.
- *For the underdemanded types:* By Assumption 1, there will be an arbitrarily large number of underdemanded pairs. Hence, the number of underdemanded pairs is always ∞ .
- *For the self-demanded types:* Whenever a self-demanded pair i of type $V-V \in \mathcal{P}^S$ is available in the exchange pool, as an implication of Corollary 1, the decisions may be complicated by the existence of other self-demanded and reciprocally demanded type pairs in the same compatibility level. Selection of other pairs in an exchange may affect which self-demanded type pairs will be used if different type pairs are simultaneously available. A self-demanded type can never save an underdemanded or reciprocally demanded pair without the help of an overdemanded or reciprocally demanded pair(s) by Proposition 2. On the other hand, if there is more than one such type of a pair, then we can match all such pairs together in an exchange. This and the above observations imply that under an efficient matching mechanism, for any $V-V \in \mathcal{P}^S$, at steady-state there will be either zero or one $V-V$ type pair.

Therefore, self-demanded types' effect to the reduced state space will be reflected by four additional state variables, each getting values of either 0 or 1. We first derive the efficient dynamic matching mechanism by ignoring the self-demanded type pairs; then we will reintroduce the self-demanded types to the problem and comment on the dynamically efficient matching mechanism for our leading example of kidney exchanges in Appendix B.

Assumption 3 (No self-demanded types assumption). *There are no self-demanded types available for exchange and $p_{V-V} = 0$ for all $V-V \in \mathcal{P}$.*

- *For the reciprocally demanded types:* By the above analyses, there are no overdemanded and self-demanded type pairs available and there are infinitely many underdemanded type

16. When there is a W_2-W_1 type pair, we can immediately match this pair with the W_1-W_2 type pair. Thus suppose that there is no W_2-W_1 pair available in the pool.

17. If there are also W_1-W_1 and W_2-W_2 type pairs existent in the pool, then the decision is between

- an n -way exchange without a W_1-W_2 type pair and with one of the two self-demanded pairs, and
- an $n + 2$ -way exchange that additionally matches a W_1-W_2 type pair and the other self-demanded pair.

18. See Puterman (1994) for an excellent survey of continuous-time and discrete-time Markov decision processes.

19. Since the pairs arrive according to a Poisson process, which is memory-less, solving the problem only for this Markov decision process with $|\mathcal{P}|$ variables will also provide a solution of the original problem stated in equation (6). Moreover, this solution will be independent of other characteristics such as the inflow and match history of the exchange, time, and initial conditions.

pairs. Therefore, the state of the exchange pool can simply be denoted by the number of reciprocally demanded pairs. On the other hand, any reciprocally demanded pairs of types W_1-W_2 and $W_2-W_1 \in \mathcal{P}^R$ can be matched in a two-way exchange. Moreover, by Proposition 2, a reciprocally demanded type pair cannot save an underdemanded pair in an exchange without the help of an overdemanded pair. Hence, the most efficient use of W_1-W_2 and W_2-W_1 type pairs is to be matched with each other in a two-way exchange. Therefore, under the efficient matching mechanism, a W_1-W_2 and W_2-W_1 type pair will never remain in the pool together, but will be matched via a two-way exchange.

Let $\mathcal{P}^{R*} \subseteq \mathcal{P}^R$ be fixed such that for all $W_1-W_2 \in \mathcal{P}^{R*}$

$$W_1-W_2 \in \mathcal{P}^{R*} \iff W_2-W_1 \notin \mathcal{P}^{R*}. \tag{12}$$

That is, for each compatibility level with two object types W_1 and W_2 , only one pair type W_1-W_2 is in \mathcal{P}^{R*} .

By the above observation, we can simply denote the state of the exchange pool by an integer vector $s = (s_{W_1-W_2})_{W_1-W_2 \in \mathcal{P}^{R*}}$, such that for all $W_1-W_2 \in \mathcal{P}^{R*}$, if $s_{W_1-W_2} > 0$, then $s_{W_1-W_2}$ refers to the number of W_1-W_2 type pairs in the exchange pool, and if $s_{W_1-W_2} < 0$, then $|s_{W_1-W_2}|$ refers to the number of W_2-W_1 type pairs in the exchange pool. Formally, $s_{W_1-W_2}$ is the difference between the number of W_1-W_2 type pairs and W_2-W_1 type pairs in the pool, and *only one of these two numbers can be non-zero*. Let $S = \mathbb{Z}^{|\mathcal{P}^{R*}|}$ be the state space.

In our running example explored in Figure 1(a), we can set $\mathcal{P}^{R*} = \{A_1-A_2, D_1-D_2\}$ and $S = \mathbb{Z}^2$.

4.1. Markov chain representation

In this subsection, we characterize the transition from one state to another under a dynamically efficient matching mechanism by a Markov chain when Assumptions 1, 2, and 3 hold:

Fix $W_1-W_2 \in \mathcal{P}^{R*}$. By Corollary 1, the decisions regarding pairs of types W_1-W_2 and W_2-W_1 are independent from decisions regarding other reciprocal types. Therefore, we focus just on W_1-W_2 and W_2-W_1 type pairs. Hence, we consider the state (component) of the pool regarding W_1-W_2 and W_2-W_1 types, $s_{W_1-W_2}$. Suppose that $s_{W_1-W_2} > 0$, i.e. there are only W_1-W_2 type pairs in the pool, but no W_2-W_1 type pairs. We define the following partition of the overdemanded pairs:

$$\begin{aligned} \mathcal{P}^O(W_1-W_2) &= \{X-Y \in \mathcal{P}^O : W_2 \blacktriangleright X \text{ and } Y \blacktriangleright W_1\}, \\ \mathcal{P}^O(\sim W_1-W_2) &= \mathcal{P}^O \setminus \mathcal{P}^O(W_1-W_2). \end{aligned} \tag{13}$$

By Proposition 2, $\mathcal{P}^O(W_1-W_2)$ is the set of overdemanded pairs that are required to match W_1-W_2 type pairs; and $\mathcal{P}^O(\sim W_1-W_2)$ is the set of remaining overdemanded pairs.

Next, we will analyse decisions regarding W_1-W_2 type pairs:

Assume that an $X-Y$ type pair arrives. Three cases are possible regarding $X-Y$:

1. $X-Y \in \mathcal{P}^O$: By Assumption 2 and Proposition 3, we need to match the $X-Y$ type pair immediately. Moreover, we need to match L_X-L_Y underdemanded type pairs in such an exchange; otherwise, such an exchange will not be efficient by Assumption 1 and Corollary 1. We isolate ourselves from all decisions regarding any type of reciprocally demanded pairs, but W_1-W_2 and W_2-W_1 type pairs. Suppose that E is a feasible n -way

exchange for some $n \geq 2$ that can match L_X-L_Y underdemanded pairs, the $X-Y$ type pair i , and possibly some reciprocally demanded pairs in an efficient way, but no W_1-W_2 type pairs. We have two cases regarding the decision for W_1-W_2 type pairs:

- $X-Y \in \mathcal{P}^O (\sim W_1-W_2)$: By Proposition 2 and the fact that there are no W_2-W_1 pairs in the pool, there is no feasible exchange that can match a W_1-W_2 type pair. Thus, exchange E is an efficient exchange.
 - $X-Y \in \mathcal{P}^O (W_1-W_2)$: By Corollary 1, instead of exchange E , we can conduct an $(n + 1)$ -way exchange, E' , including the overdemanded and reciprocally demanded type pairs, the same number of underdemanded type pairs, and one more reciprocally demanded pair from the W_1-W_2 type. In this case, we have two possible actions: conduct exchange E (smaller exchange) or conduct exchange E' (larger exchange). If E' is conducted, the state component for W_1-W_2 and W_2-W_1 type pairs decreases to $s_{W_1-W_2} - 1$, since one fewer W_1-W_2 type pair will remain in the exchange pool.
2. $X-Y \in \mathcal{P}^U$: By Assumption 2 and Proposition 3, there are no overdemanded pairs available in the pool. And by Proposition 2, no exchanges are feasible.
 3. $X-Y \in \mathcal{P}^R$: Three cases are possible:
 - $X-Y = W_1-W_2$: Since there are no W_2-W_1 type pairs, and no overdemanded pairs (by Assumption 2 and Proposition 3), by Proposition 2, there are no feasible exchanges, and the state component for W_1-W_2 and W_2-W_1 type pairs increases to $s_{W_1-W_2} + 1$.
 - $X-Y = W_2-W_1$: A two-way exchange can be conducted using a W_1-W_2 type pair in the pool and the arriving $X-Y$ type pair i . This is the only feasible type of exchange. Since matching a W_2-W_1 type pair with a W_1-W_2 type pair is the most efficient use of these types of pairs, we need to conduct such a two-way exchange. The state component for W_1-W_2 and W_2-W_1 type pairs decreases to $s_{W_1-W_2} - 1$.
 - $X-Y \notin \{W_1-W_2, W_2-W_1\}$: By Proposition 2, there is no feasible exchange regarding W_1-W_2 type pairs.

Figure 3 summarizes how the state of the pool regarding W_1-W_2 and W_2-W_1 type pairs evolves for $s_{W_1-W_2} > 0$.

For $s_{W_1-W_2} < 0$, i.e. when $|s_{W_1-W_2}|$ W_2-W_1 type pairs are available in the exchange pool, we observe the symmetric version of the above evolution. For $s_{W_1-W_2} = 0$, i.e. when there are no W_1-W_2 and W_2-W_1 type pairs available in the exchange pool, the evolution is somewhat simpler. Figure 4 summarizes the transitions from state component $s_{W_1-W_2} = 0$. The only state transition regarding $s_{W_1-W_2}$ occurs when a W_1-W_2 type pair arrives (to state component $s_{W_1-W_2} = 1$), or when a W_2-W_1 type pair arrives (to state component $s_{W_1-W_2} = -1$).

4.2. Bellman equations

In this subsection, we derive the Bellman equations that will be used to find the efficient matching mechanism. Let τ_1 be the time between two arrivals. Since the arrival process is a Poisson process with arrival rate λ , where λ is the expected number of arrivals in unit time, then τ_1 is distributed with an exponential distribution with parameter λ , that is, the probability density function of τ_1 is $\lambda e^{-\lambda\tau_1}$. Then, the expected total discounting that occurs until a new pair arrives is given by

$$E [e^{-\rho\tau_1}] = \int_0^\infty \lambda e^{-\rho\tau_1} e^{-\lambda\tau_1} d\tau_1 = \frac{\lambda}{\lambda + \rho}. \tag{14}$$

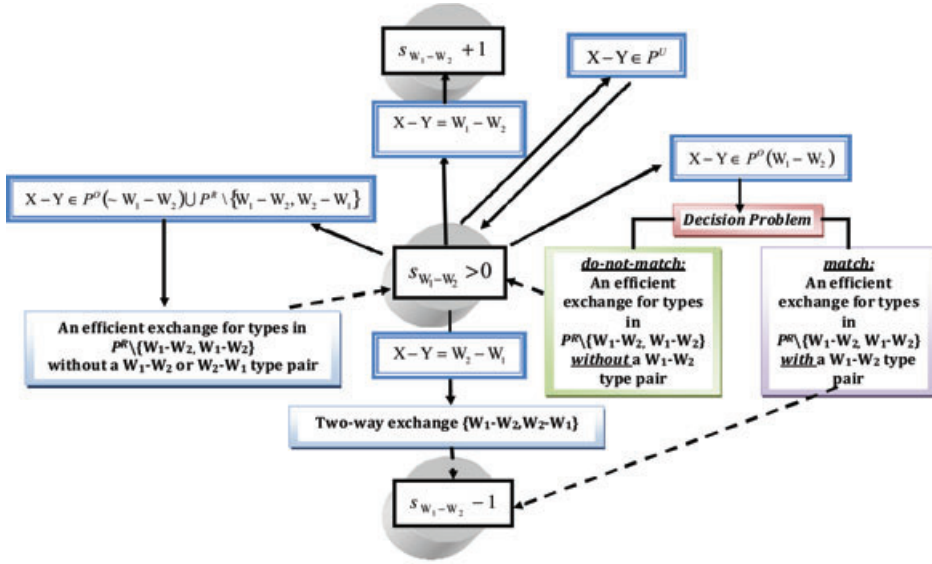


FIGURE 3
Transitions with arrivals when $s_{w_1-w_2} > 0$

When a pair is matched in the exchange pool, the surplus related to the pair is $\int_0^\infty ce^{-\rho\tau} d\tau = \frac{c}{\rho}$.²⁰

Using the analyses in the previous subsection, under Assumptions 1, 2, and 3, we can state Bellman equations for the reduced continuous time Markov process. By Proposition 2 and Corollary 1, $ES(s)$, the total surplus at state $s \in S$ under the efficient rule can be written as the sum of surpluses regarding each type:

$$ES(s) = \sum_{X-Y \in \mathcal{P}^O} ES_{X-Y} + \sum_{V-V \in \mathcal{P}^S} ES_{V-V} + \sum_{W_1-W_2 \in \mathcal{P}^{R^*}} ES_{W_1-W_2}(s_{W_1-W_2}) \quad (15)$$

where

- ES_{X-Y} for each type $X-Y \in \mathcal{P}^O$ is equal to $\frac{\lambda p_{X-Y}}{\rho} (L_X - L_Y + 1) \frac{c}{\rho}$ where $\sum_{m=1}^\infty \left(\frac{\lambda p_{X-Y}}{\lambda p_{X-Y} + \rho}\right)^m = \frac{\lambda p_{X-Y}}{\rho}$ is the expected total discounting related to all future incoming $X-Y$ type pairs, $L_X - L_Y$ is the number of underdemanded type pairs, and 1 is the number of the overdemanded pair that can be matched regardless of the reciprocally demanded pairs matched. Since underdemanded types cannot be matched without the help of overdemanded types (by Proposition 2), we incorporate their surplus to the surplus of overdemanded types.
- $ES_{V-V} = 0$ for all $V-V \in \mathcal{P}^S$ by Assumption 3.
- $ES_{W_1-W_2}(s_{W_1-W_2})$ is the surplus related to reciprocally demanded types W_1-W_2 and W_2-W_1 , for each $W_1-W_2 \in \mathcal{P}^{R^*}$ and $s_{W_1-W_2} \in \mathbb{Z}$. It can be maximized independently from other surpluses $ES_{W_3-W_4}(s_{W_3-W_4})$ for all $W_3-W_4 \in \mathcal{P}^{R^*} \setminus \{W_1-W_2\}$ and $s_{W_3-W_4} \in \mathbb{Z}$ by Corollary 1.

20. We will later observe that the optimal matching mechanism is independent of how this individual surplus is calculated. Thus, it is robust to the interpretation of surplus.

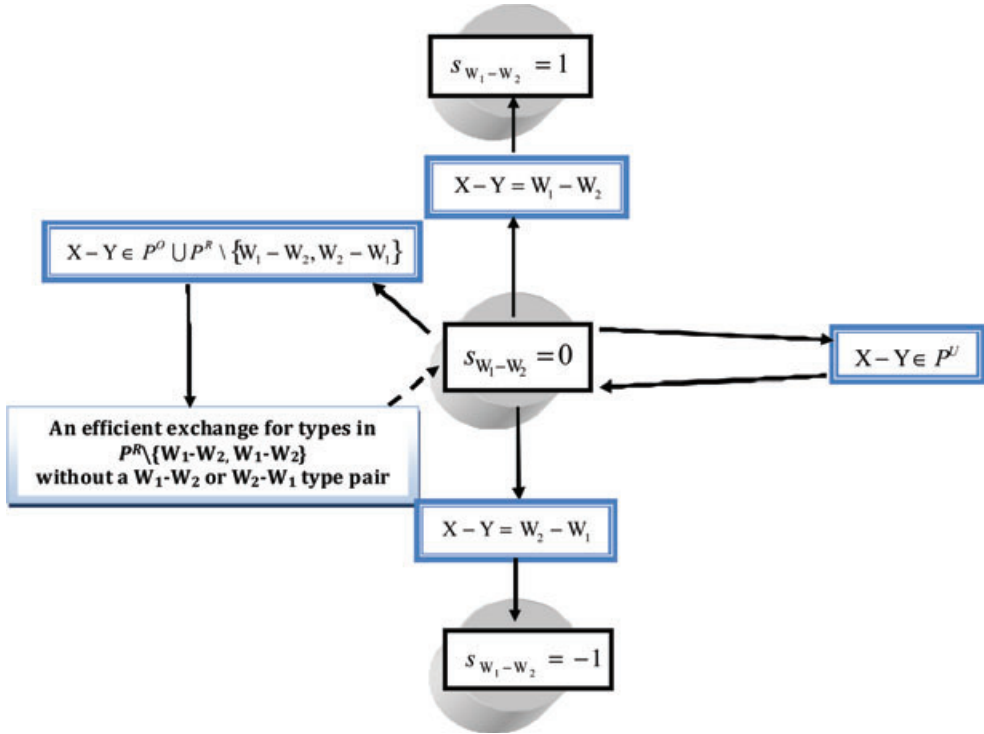


FIGURE 4
Transitions with arrivals when $s_{W_1 - W_2} = 0$

From now on, we focus on the exchange surplus related to reciprocally demanded types. Fix $W_1 - W_2 \in \mathcal{P}^{R^*}$. For $s_{W_1 - W_2} > 0$, exchange surplus for types $W_1 - W_2$ and $W_2 - W_1$ is stated as

$$\begin{aligned}
 & ES_{W_1 - W_2}(s_{W_1 - W_2}) \\
 &= \frac{\lambda}{\lambda + \rho} \left[\begin{aligned} & \left(\sum_{X - Y \in \mathcal{P}^O \setminus (W_1 - W_2) \cup \mathcal{P}^U \cup \mathcal{P}^R \setminus \{W_1 - W_2, W_2 - W_1\}} p_{X - Y} \right) ES_{W_1 - W_2}(s_{W_1 - W_2}) \\ & + \left(\sum_{X - Y \in \mathcal{P}^O(W_1 - W_2)} p_{X - Y} \right) \max \left\{ ES_{W_1 - W_2}(s_{W_1 - W_2}), ES_{W_1 - W_2}(s_{W_1 - W_2} - 1) + \frac{c}{\rho} \right\} \\ & + p_{W_1 - W_2} ES_{W_1 - W_2}(s_{W_1 - W_2} + 1) + p_{W_2 - W_1} \left(ES_{W_1 - W_2}(s_{W_1 - W_2} - 1) + \frac{2c}{\rho} \right) \end{aligned} \right]. \tag{16}
 \end{aligned}$$

On the right-hand side of equation (16) (1) the first row considers the case when an overdemanded pair that cannot be used in matching a $W_1 - W_2$ type pair or an underdemanded pair or a reciprocally demanded pair of types other than $W_1 - W_2$ and $W_2 - W_1$ arrives; (2) the second row considers the case when an overdemanded pair that can be used in matching a $W_1 - W_2$ type pair arrives, leading to a decision of either matching the $W_1 - W_2$ type pair or not together with the efficient size exchanges decided for other types; and (3) the third row considers the case when a $W_1 - W_2$ type pair arrives, leading to an increase in the state component, and when

a W_2-W_1 type pair arrives, reducing the state component by conducting a two-way exchange and matching one W_2-W_1 and one W_1-W_2 type pairs.

We can rewrite equation (16) by dividing both sides of the equation by $\frac{c}{\rho}$ and setting $ES_{W_1-W_2}^*(s_{W_1-W_2}) = \frac{\rho}{c} ES_{W_1-W_2}(s_{W_1-W_2})$ as follows:

$$ES_{W_1-W_2}^*(s_{W_1-W_2}) = \frac{\lambda}{\lambda + \rho} \left[\begin{aligned} & \left(\sum_{X-Y \in \mathcal{P}^O \cap (W_1-W_2) \cup \mathcal{P}^U \cup \mathcal{P}^R \setminus \{W_1-W_2, W_2-W_1\}} p_{X-Y} \right) ES_{W_1-W_2}^*(s_{W_1-W_2}) \\ & + \left(\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} \right) \max \left\{ ES_{W_1-W_2}^*(s_{W_1-W_2}), ES_{W_1-W_2}^*(s_{W_1-W_2} - 1) + 1 \right\} \\ & + p_{W_2-W_1} ES_{W_1-W_2}^*(s_{W_1-W_2} + 1) + p_{W_1-W_2} \left(ES_{W_1-W_2}^*(s_{W_1-W_2} - 1) + 2 \right) \end{aligned} \right] \tag{17}$$

Note that since by Assumption 3, $p_{V-V} = 0$ for all $V-V \in \mathcal{P}^S$, we have

$$\sum_{X-Y \in \mathcal{P}^O \cap (W_1-W_2) \cup \mathcal{P}^U \cup \mathcal{P}^R \setminus \{W_1-W_2, W_2-W_1\}} p_{X-Y} = 1 - \left(\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} \right) - p_{W_1-W_2} - p_{W_2-W_1}.$$

Similarly, we can write the Bellman equation for state components $s_{W_1-W_2} < 0$ as follows:

$$ES_{W_1-W_2}^*(s_{W_1-W_2}) = \frac{\lambda}{\lambda + \rho} \left[\begin{aligned} & \left(\sum_{X-Y \in \mathcal{P}^O \cap (W_2-W_1) \cup \mathcal{P}^U \cup \mathcal{P}^R \setminus \{W_1-W_2, W_2-W_1\}} p_{X-Y} \right) ES_{W_1-W_2}^*(s_{W_1-W_2}) \\ & + \left(\sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y} \right) \max \left\{ ES_{W_1-W_2}^*(s_{W_1-W_2}), ES_{W_1-W_2}^*(s_{W_1-W_2} + 1) + 1 \right\} \\ & + p_{W_2-W_1} ES_{W_1-W_2}^*(s_{W_1-W_2} - 1) + p_{W_1-W_2} \left(ES_{W_1-W_2}^*(s_{W_1-W_2} + 1) + 2 \right) \end{aligned} \right] \tag{18}$$

For state component 0, the Bellman equation is

$$ES_{W_1-W_2}^*(0) = \frac{\lambda}{\lambda + \rho} \left[\begin{aligned} & \left(\sum_{X-Y \in \mathcal{P}^O \cup \mathcal{P}^U \cup \mathcal{P}^R \setminus \{W_1-W_2, W_2-W_1\}} p_{X-Y} \right) ES_{W_1-W_2}^*(0) \\ & + p_{W_1-W_2} ES_{W_1-W_2}^*(1) + p_{W_2-W_1} \left(ES_{W_1-W_2}^*(-1) \right) \end{aligned} \right] \tag{19}$$

The following observations will be useful for our analysis in the next section. They follow from the formulation of the problem.

Observation 2. *If an overdemanded pair that can be used to match a W_1-W_2 pair arrives and yet the smaller exchange without any W_1-W_2 type pair is chosen at a state component $s_{W_1-W_2} > 0$, then $ES_{W_1-W_2}^*(s_{W_1-W_2}) \geq ES_{W_1-W_2}^*(s_{W_1-W_2} - 1) + 1$. If the larger exchange with a W_1-W_2 type pair is chosen, then $ES_{W_1-W_2}^*(s_{W_1-W_2}) \leq ES_{W_1-W_2}^*(s_{W_1-W_2} - 1) + 1$.*

Observation 3. *If an overdemanded pair that can be used to match a W_2-W_1 pair arrives and yet the smaller exchange without any W_2-W_1 type pair is chosen at a state component*

$s_{W_1-W_2} < 0$, then $ES_{W_1-W_2}^*(s_{W_1-W_2}) \geq ES_{W_1-W_2}^*(s_{W_1-W_2} + 1) + 1$. If the larger exchange with a W_2-W_1 type pair is chosen, then $ES_{W_1-W_2}^*(s_{W_1-W_2}) \leq ES_{W_1-W_2}^*(s_{W_1-W_2} + 1) + 1$.

The solution for $ES_{W_1-W_2}^*(s_{W_1-W_2})$ in equations (17), (18), and (19) gives the normalized efficient exchange surplus regarding W_1-W_2 and W_2-W_1 type reciprocally demanded pairs. Does a solution exist to these equations, and if so, is it unique? The following proposition answers this question affirmatively. It is proven in Appendix A.

Proposition 4. For any $W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}$, there exists a unique solution $ES_{W_1-W_2}^* : \mathbb{Z} \rightarrow \mathbb{R}_+$ to the Bellman equations given in equations (17), (18), and (19).

4.3. The efficient matching mechanism

A (deterministic) Markov matching mechanism ϕ is a matching mechanism that chooses the same action whenever the Markov chain is in the same state. In our reduced state and action problem, a Markov matching mechanism makes multiple decisions at a state depending on the type of an arriving pair and the number and the types of reciprocally demanded pairs in the pool. For each reciprocally demanded type W_1-W_2 existing in the pool, when an overdemanded type pair that can be used to match a W_1-W_2 type pair arrives, the two decisions are (a) conduct an exchange without a W_1-W_2 pair, but with the maximum possible number of underdemanded pairs (action *do-not-match*), or (b) conduct an exchange with a W_1-W_2 pair and the maximum possible number of underdemanded pairs (action *match*). The remaining choices of the Markov mechanism are straightforward: it chooses an exchange with the maximum number of underdemanded pairs when such an exchange becomes feasible as outlined in Figure 3 for positive states, Figure 4 for state zero, and the symmetric version of Figure 3 for negative states. Formally, $\phi : S \rightarrow \{do-not-match, match\}^{|\mathcal{P}^{\mathcal{R}^*}|}$ is a Markov matching mechanism.

A Markov matching mechanism $\phi^{\bar{s}, \underline{s}} : S \rightarrow \{do-not-match, match\}^{|\mathcal{P}^{\mathcal{R}^*}|}$ is a threshold matching mechanism with thresholds $\bar{s}, \underline{s} \in S$ with $\underline{s} \leq 0$ and $\bar{s} \geq 0$, if for any $W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}$,

$$\phi_{W_1-W_2}^{\bar{s}, \underline{s}}(s) = \begin{cases} do-not-match & \text{if } \underline{s}_{W_1-W_2} \leq s_{W_1-W_2} \leq \bar{s}_{W_1-W_2} \\ match & \text{if } s_{W_1-W_2} < \underline{s}_{W_1-W_2} \text{ or } s_{W_1-W_2} > \bar{s}_{W_1-W_2} \end{cases}, \quad (20)$$

where $\phi^{\bar{s}, \underline{s}}(s) = (\phi_{W_1-W_2}^{\bar{s}, \underline{s}}(s))_{W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}}$.

When an overdemanded pair arrives, a threshold matching mechanism conducts the largest exchange that does not use existing W_1-W_2 or W_2-W_1 type pairs (*do-not-match* option) as long as the number of W_1-W_2 or W_2-W_1 type pairs is not greater than the threshold numbers, $\bar{s}_{W_1-W_2}$ and $|\underline{s}_{W_1-W_2}|$, respectively; otherwise, it conducts the largest possible exchanges including the existing W_1-W_2 or W_2-W_1 type pairs (*match* option).

Our main theorem of this section is as follows:

Theorem 2. Suppose Assumptions 1, 2, and 3 hold. There exist $\bar{s}_{W_1-W_2}^* = 0$ and $\underline{s}_{W_1-W_2}^* \leq 0$, or $\bar{s}_{W_1-W_2}^* \geq 0$ and $\underline{s}_{W_1-W_2}^* = 0$ for each $W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}$ such that $\phi^{\bar{s}^*, \underline{s}^*}$ is a dynamically efficient multi-way matching mechanism.

The proof of Theorem 2 is in Appendix A. Through this theorem, we show that there exists a dynamically efficient matching mechanism, which is a special kind of a threshold mechanism. It stocks W_1-W_2 or W_2-W_1 type pairs, and does not use them in larger exchanges as long as the stock of the control group is less than or equal to $\bar{s}_{W_1-W_2}^*$ or $|\underline{s}_{W_1-W_2}^*|$, respectively. Either

the number of W_1-W_2 type pairs or W_2-W_1 type pairs is the state variable, but not both. Under the first type of solution, the number of W_2-W_1 type pairs is the state variable. As long as the number of W_2-W_1 type pairs in the pool is zero, regardless of the number of W_1-W_2 type pairs, when the next arrival of an overdemanded pair occurs, the first type of efficient mechanism conducts the maximal size exchanges possible. If there are W_2-W_1 type pairs and their number does not exceed the threshold number $|\underline{s}_{W_1-W_2}^*|$, then these pairs are exclusively used to match incoming W_1-W_2 type pairs in two-way exchanges. On the other hand, if the number of W_2-W_1 type pairs exceeds the threshold number $|\underline{s}_{W_1-W_2}^*|$, they should be used in maximal exchanges which can be (1) a two-way exchange involving a W_1-W_2 type pair if the incoming pair type is W_1-W_2 , or (2) a multi-way exchange involving an overdemanded pair in $\mathcal{P}^O(W_2-W_1)$. The other types of maximal exchanges are conducted by the efficient mechanism as soon as they become feasible. The second possible solution is the symmetric version of the above mechanism taking the number of W_1-W_2 type pairs as a state variable.

Next, we specify the efficient mechanism more precisely.

Theorem 3. *Suppose Assumptions 1, 2, and 3 hold. Let $W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}$. Suppose that $\phi^{\bar{s}^*, \underline{s}^*}$ is an efficient multi-way matching mechanism.*

- *If $p_{W_1-W_2} \geq p_{W_2-W_1}$, that is, the W_1-W_2 type arrives at least as frequently as the W_2-W_1 type, and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} < \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$, that is, the overdemanded types that can match W_1-W_2 type pairs in larger exchanges arrive less frequently than those for the W_2-W_1 type, then $\underline{s}_{W_1-W_2}^* \leq 0$ and $\bar{s}_{W_1-W_2}^* = 0$.*
- *If $p_{W_1-W_2} = p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} = \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$, then $\underline{s}_{W_1-W_2}^* = 0$ and $\bar{s}_{W_1-W_2}^* = 0$, i.e. maximal size exchanges are conducted whenever they become feasible.*
- *If $p_{W_1-W_2} \leq p_{W_2-W_1}$, and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} > \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$, then $\underline{s}_{W_1-W_2}^* = 0$ and $\bar{s}_{W_1-W_2}^* \geq 0$.*

Proof of Theorem 2. Let Assumptions 1, 2, and 3 hold. Let $W_1-W_2 \in \mathcal{P}^{\mathcal{R}^*}$.

- Let $p_{W_1-W_2} \geq p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} < \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$. By Theorem 2, threshold mechanism $\phi^{\bar{s}^*, \underline{s}^*}$ is efficient. Hence, we have $\bar{s}_{W_1-W_2}^* = 0$ and $\underline{s}_{W_1-W_2}^* \leq 0$, or $\bar{s}_{W_1-W_2}^* \geq 0$ and $\underline{s}_{W_1-W_2}^* = 0$ such that $\phi^{\bar{s}^*, \underline{s}^*}$ is a dynamically efficient multi-way matching mechanism. If we conducted maximal number of exchanges at every state, there will be excess W_1-W_2 type pairs on average remaining at the pool. Suppose $\underline{s}_{W_1-W_2}^* > 0$. We will have even more excess W_1-W_2 type pairs on average, since we do not always match them in larger exchanges. Therefore, the expected surplus under mechanism $\phi^{(\bar{s}^*(W_1-W_2), 0), (\underline{s}^*(W_1-W_2), 0)}$ is higher than under mechanism $\phi^{\bar{s}^*, \underline{s}^*}$, contradicting the claim that the latter one is efficient. Thus, $\bar{s}_{W_1-W_2}^* = 0$. By Theorem 2, $\underline{s}_{W_1-W_2}^* \leq 0$.
- Let $p_{W_1-W_2} = p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} = \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$. Then, the Bellman equations stated in equation (17) for positive states and in equation (18) for negative states are completely symmetric, implying that $ES_{W_1-W_2}^*(s_{W_1-W_2}) = ES_{W_1-W_2}^*(-s_{W_1-W_2})$ for any $s_{W_1-W_2} \in \mathbb{Z}$. Suppose that $\underline{s}_{W_1-W_2}^* < 0$. Then at state component -1 regarding W_1-W_2 types, the *do-not-match* option is executed. By Observation 3, we have $ES_{W_1-W_2}^*(-1) \geq ES_{W_1-W_2}^*(0) + 1$. Then, $ES_{W_1-W_2}^*(1) = ES_{W_1-W_2}^*(-1) \geq ES_{W_1-W_2}^*(0) + 1$ as well, implying together with Observation 3 that the *do-not-match* option is executed for W_1-W_2 type pairs at state component 1, and that

$\bar{s}_{W_1-W_2}^* > 0$. However, $\underline{s}_{W_1-W_2}^* < 0$ and $\bar{s}_{W_1-W_2}^* > 0$ contradict Theorem 2. Therefore, $\underline{s}_{W_1-W_2}^* = 0$. With the symmetric argument, we show that $\bar{s}_{W_1-W_2}^* = 0$.

- Let $p_{W_1-W_2} \leq p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} > \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$. The symmetric argument of the first part of the proof holds. ||

The intuition behind Theorem 3 can be stated as follows: W_1-W_2 (W_2-W_1) type pairs are most efficiently used in matching W_2-W_1 (W_1-W_2) type pairs in two-way exchanges. This is true because, by Proposition 2, these two reciprocally demanded pair types cannot be used to save any underdemanded type pairs. Moreover, the use of overdemanded pairs exclusively to save W_1-W_2 and W_2-W_1 type pairs is costly, since they can instead be used to save underdemanded pairs which are abundant. Consider a situation in which $p_{W_1-W_2} \geq p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} < \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$, that is, the types that can be used to serve W_1-W_2 type pairs arrive less frequently than the types that can be used to serve W_2-W_1 type pairs. Under these two conditions, *W_2-W_1 type pairs do not arrive as frequently as W_1-W_2 type pairs, and W_2-W_1 type pairs can be used more frequently in larger exchanges.* Consider a positive state component of the pool regarding W_1-W_2 and W_2-W_1 types, i.e. there are W_1-W_2 type pairs. Since W_2-W_1 type pairs arrive *on average* less frequently than W_1-W_2 type pairs for two-way exchanges, whenever an overdemanded pair that can serve a W_1-W_2 type pair arrives, the W_1-W_2 type pairs can safely be used in larger exchanges. On the other hand, if the state component of the pool regarding W_1-W_2 and W_2-W_1 types is negative, i.e. there are W_2-W_1 type pairs, since W_1-W_2 type pairs arrive *on average* more frequently for two-way exchanges, this means that the average arrival process is interrupted, and we end up with some excess W_2-W_1 type pairs. So, we have a higher option value for keeping W_2-W_1 type pairs than matching them in larger exchanges. We should have a positive stock of W_2-W_1 type pairs in hand to match them exclusively with future coming W_1-W_2 type pairs.²¹ On the other hand, if $p_{W_1-W_2} = p_{W_2-W_1}$ and $\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} = \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y}$, on average W_1-W_2 and W_2-W_1 types arrive at the same rate exclusively for two-way exchanges. Therefore, using existing W_1-W_2 or W_2-W_1 type pairs in larger exchanges instead of matching with incoming reciprocal pairs has no expected future costs. Thus, we do not need to worry about carrying a positive stock of W_1-W_2 or W_2-W_1 type pairs.

5. DYNAMICALLY EFFICIENT KIDNEY EXCHANGE

The kidney exchange problem is a special case of the general model that we considered above. In this problem, we refer to an object-agent pair as a recipient-donor pair. The type space for kidney needs is defined through blood- and tissue-type compatibility.

Before a donor is deemed compatible with a recipient, two tests are required: a blood-type compatibility test and a tissue-type compatibility test (or cross-match test). There are four blood types, O, A, B, and AB. An O blood type recipient can only receive a transplant from an O donor, an A blood type recipient can only receive a transplant from an O or an A donor, a B blood type recipient can only receive a transplant from an O or a B donor, and an AB blood type recipient can receive a transplant from all donors. A recipient and a donor are *blood-type compatible* if the donor can feasibly donate a kidney to the recipient based on their blood types.

21. Since there is discounting and the number of W_2-W_1 type pairs can only be an integer, sometimes the threshold can be 0 instead of a positive number.

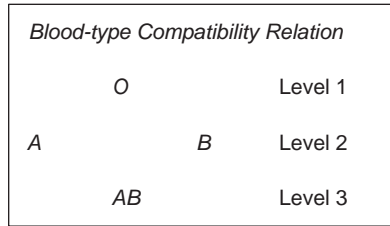


FIGURE 5

Blood-type compatibility relation (also see Figure 1(b))

Observe that the blood-type compatibility relation forms a partial order with three levels of compatibility. The O blood type is located at the highest level at level 1, the A and B blood types are located at level 2, and the AB blood type is at level 3 (see Figure 5).

There is yet another type of incompatibility for kidney recipients. Sometimes a recipient cannot receive a kidney from a blood-type compatible donor due to tissue-type incompatibility. There are six proteins on human DNA that determine the tissue type of a person. Some tissue types can be rejected by a recipient's immunological system. A formal test is done by mixing the blood of the donor and the recipient for testing tissue-type incompatibility prior to the transplant. If antibodies form in the recipient's blood against the donor's tissue antigens, then there is *positive cross-match* between the recipient and the donor, meaning that the donor and the recipient are tissue-type incompatible. A donor is *tissue-type compatible* with a recipient if there is negative cross-match between them. A donor is *compatible* with a recipient if he is both blood- and tissue-type compatible with the recipient. A recipient can receive a kidney only from compatible donors.

Usually, when a donor is compatible with his paired recipient, such a pair does not participate in exchange since the donor directly donates his kidney to the recipient. Hence, a blood-type compatible pair becomes available for exchange if and only if the pair is tissue-type incompatible. For tissue-type incompatibility between the donors and patients of different pairs, we will make an additional assumption. This will give us an idea on limits of kidney exchange (see Roth, Sönmez and Ünver, 2007):

Assumption 4 (Limit assumption). *No recipient is tissue-type incompatible with the donor of another pair.*

Recipients can be tissue-type incompatible with their own donors, and we assume that $p_c > 0$ is the probability for that to happen. This ensures that blood-type compatible pairs arrive at the pool. On the other hand, recipients will never be tissue-type incompatible with donors of other pairs under Assumption 4; thus, two pairs will be mutually compatible if and only if they are mutually blood-type compatible. Note that average tissue-type incompatibility (positive cross-match) probability is reported as $p_c = 0.11$ by Zenios, Woodle and Ross (2001).

We will continue to maintain Assumptions 1, 2, and 3 for kidney exchanges as well. In Section 5.2.1, we show that these assumptions are plausible for kidney exchange. We also comment on what happens when these assumptions are relaxed in Section 5.2.1 and in Appendix B.

5.1. The efficient kidney exchange mechanism

We are ready to present the pair type space for kidney exchanges. The blood types give the compatibility type of each recipient and donor (under Assumption 4). Therefore, the type of a pair is represented by the blood type of the recipient and the blood type of the donor in the pair. There are 16 pair types. We state the overdemanded, underdemanded, self-demanded, and reciprocally demanded types as follows:

$$\begin{aligned}
 \mathcal{P}^O &= \{A-O, B-O, AB-O, AB-A, AB-B\} \\
 \mathcal{P}^U &= \{O-A, O-B, O-AB, A-AB, B-AB\} \\
 \mathcal{P}^S &= \{O-O, A-A, B-B, AB-AB\} \\
 \mathcal{P}^R &= \{A-B, B-A\}.
 \end{aligned}
 \tag{21}$$

Since there are only two reciprocally demanded types, we can represent the reduced Markov chain using a single integer s representing the number of A-B type pairs if $s > 0$ and the number of B-A type pairs if $s < 0$. Hence, the state space is the set of integers, i.e. $S = \mathbb{Z}$. In Figures 6 and 7, the exchange options and their trade-offs in the decision problem are depicted when there are B-A type pairs in the pool and an overdemanded pair in $\mathcal{P}^O(B-A) = \{A-O, AB-B, AB-O\}$ arrives. Also, note that $\mathcal{P}^O(A-B) = \{B-O, AB-A, AB-O\}$. The options regarding the case with A-B type pairs are just the symmetric versions of the options with B-A type pairs.

By Theorem 2, under Assumptions 1, 2, 3, and 4, the efficient mechanism is given by a threshold Markov mechanism, $\phi^{\bar{s}^*, \underline{s}^*} : \mathbb{Z} \rightarrow \{do-not-match, match\}$, with $\bar{s}^* \geq 0$ and $\underline{s}^* = 0$ or $\bar{s}^* = 0$ and $\underline{s}^* \leq 0$.

The real-life arrival probabilities derived from unrelated recipient-donor matching for a pair (also used in the simulations section below) dictate $p_{B-A} \leq p_{A-B}$ and $\sum_{X-Y \in \mathcal{P}^O(A-B)} p_{X-Y} < \sum_{X-Y \in \mathcal{P}^O(B-A)} p_{X-Y}$. In this case, by Theorem 3, the efficient exchange mechanism is a threshold Markov mechanism that takes the B-A type pair number as the relevant state variable, i.e. mechanism $\phi^{0, \underline{s}^*}$ for some threshold $\underline{s}^* \leq 0$. Option *do-not-match* in Figures 6 and 7 is executed whenever there are $|s|$ B-A type pairs with $\underline{s}^* \leq s \leq 0$ and an overdemanded pair in

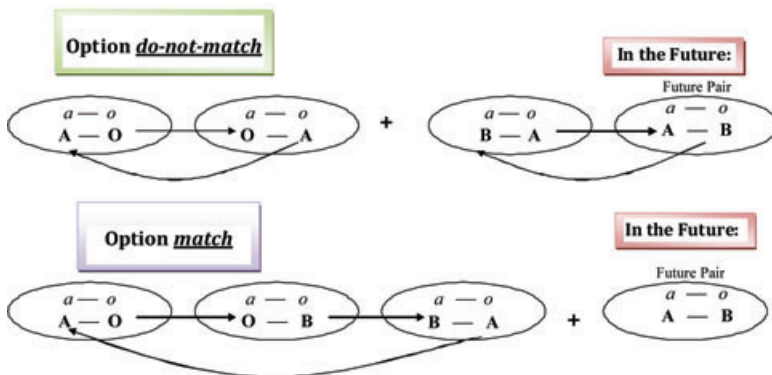


FIGURE 6

Kidney exchange options when an $A-O \in \mathcal{P}^O(B-A)$ type pair arrives and there are B-A type pairs in the exchange pool. When an $AB-B \in \mathcal{P}^O(B-A)$ type pair arrives, option *do-not-match* will involve a two-way exchange between AB-B and B-AB type pairs, and option *match* will involve a three-way exchange among AB-B, B-A, and A-AB type pairs

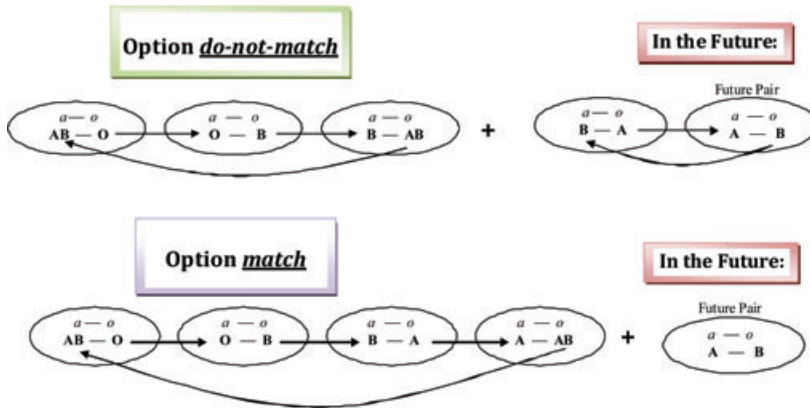


FIGURE 7
 Kidney exchange options when an $AB-O \in \mathcal{P}^O$ ($B-A$) type pair arrives and there are $B-A$ type pairs in the exchange pool. Note that another feasible exchange for option *do-not-match* is a three-way exchange with $AB-O$, $O-A$, and $A-AB$ type pairs

\mathcal{P}^O ($B-A$) arrives. Under all other states and arrivals, the maximal exchanges are conducted. For example, when $B-A$ types are available and an overdemanded pair in \mathcal{P}^O ($B-A$) arrives, option *match* in Figures 6 and 7 is conducted.

5.2. Computation of the efficient multi-way kidney exchange mechanism

In this subsection, we first formulate the underlying arrival process of incompatible pairs to the exchange pool. For any pair type $X-Y \in \mathcal{P}$, let q_{X-Y} be the probability of a random pair being of type $X-Y$. We refer to q_{X-Y} as the *arrival probability* of pair type $X-Y \in \mathcal{T}$. We have $\sum_{X-Y \in \mathcal{T}} q_{X-Y} = 1$. A compatible pair does not become available for exchange. Recall that p_c , the probability of tissue-type incompatibility, is the probability of a blood-type compatible pair being available for exchange, and 1 is the probability of a blood-type incompatible pair being available for exchange. We derive the exchange arrival probabilities of each type $X-Y$, p_{X-Y} , as follows. For each self-demanded and overdemanded type $X-Y \in \mathcal{P}^O \cup \mathcal{P}^S$, we have $p_{X-Y} = \frac{p_c q_{X-Y}}{\kappa}$, and for each underdemanded and reciprocally demanded type $X-Y \in \mathcal{P}^U \cup \mathcal{P}^R$, we have $p_{X-Y} = \frac{q_{X-Y}}{\kappa}$ where $\kappa = \sum_{X-Y \in \mathcal{P}^O \cup \mathcal{P}^S} p_c q_{X-Y} + \sum_{X-Y \in \mathcal{P}^U \cup \mathcal{P}^R} q_{X-Y}$. Thus, $\sum_{X-Y \in \mathcal{P}} p_{X-Y} = 1$.

5.2.1. Plausibility of the assumptions for kidney exchange. We comment on the efficient kidney exchange mechanism when Assumption 3 is relaxed in Appendix B, i.e. the case when self-demanded types participate in kidney exchange.

Next, we comment on the plausibility of our Assumptions 1, 2, and 4 for kidney exchange:

- Assumption 1 concerns the underlying arrival probabilities of the pairs and the applied matching mechanism. We first show that Assumption 1, i.e. having arbitrarily many underdemanded pairs in the exchange pool in the long run, is a realistic assumption:

Proposition 5. *Suppose that $p_c (q_{AB-O} + q_{X-O}) + \min \{p_c q_{Y-O}, q_{X-Y}\} < q_{O-X}$ for all $\{X, Y\} = \{A, B\}$, $p_c (q_{AB-O} + q_{AB-X}) + \min \{p_c q_{AB-Y}, q_{Y-X}\} < q_{X-AB}$ for all $\{X, Y\} = \{A, B\}$ and $p_c q_{AB-O} < q_{O-AB}$. Then, Assumption 1 holds in the long run regardless of the multi-way dynamic kidney exchange mechanism used.*

Proof of Proposition 5. By Proposition 2, underdemanded type O–A can only be matched in a two-way exchange with its reciprocal type, in an exchange using an AB–O type pair, or in an exchange using a B–O type pair and an A–B type pair such as (B–O, O–A, A–B) (see also Roth, Sönmez and Ünver, 2007). Since

$$p_c (q_{AB-O} + q_{A-O}) + \min \{p_c q_{B-O}, q_{A-B}\} < q_{O-A}, \tag{22}$$

even if all of these types, O–A, AB–O, or B–O and A–B, are used exclusively to match O–A type pairs, there will still be arbitrarily many O–A pairs left in the pool in the long run.

Similarly, an underdemanded type B–AB pair can only be matched in a two-way exchange with its reciprocal type pair, an AB–O type pair, or in an exchange using an AB–A type pair and an A–B type pair such as (AB–A, A–B, B–AB) (see also Roth, Sönmez and Ünver, 2007). Since

$$p_c (q_{AB-O} + q_{AB-B}) + \min \{p_c q_{AB-A}, q_{A-B}\} < q_{B-AB}, \tag{23}$$

even if all of AB–O, AB–B, or AB–A together with A–B type pairs are used exclusively to match B–AB type pairs, arbitrarily many B–AB type pairs will remain in the exchange pool in the long run.

Symmetric versions of these observations hold for O–B and AB–B.

By Proposition 2, an O–AB pair can only be matched using an AB–O pair. Since

$$p_c q_{AB-O} < q_{O-AB}, \tag{24}$$

even if AB–O type pairs are used exclusively to match AB–O type pairs, arbitrarily many underdemanded type pairs will remain in the long run.

Moreover, all these results are true regardless of the matching mechanism used. ||

The hypotheses of the above proposition are very mild, and will hold for sufficiently small tissue-type incompatibility (i.e. cross-match) probability p_c . Moreover, they hold for real-life blood frequencies. For example, assuming that the recipient and her paired-donor are blood-unrelated, the arrival rates reported at the end of this subsection satisfy these assumptions, when the cross-match probability is $p_c = 0.11$, as reported by Zenios, Woodle and Ross (2001).

- Assumption 2 limits the arrival rates of A–B and B–A type pairs to be close to each other. However, it does not give a measure of closeness. There is no literature reporting these rates except Terasaki, Gjertson and Cecka (1998) who report that the arrival rates of A–B and B–A type pairs as $q_{A-B} = 0.05$ and $q_{B-A} = 0.03$ but do not explain from which sample these are obtained. Under independent sampling conditions, we would expect these rates to be equal to each other.
- Assumption 4 is a limit assumption. However, it is also a somewhat realistic assumption for certain cases. If the recipient is female and has previously borne the child of her paired-donor, then her body is more likely to reject her paired-donor’s kidney than other random kidneys due to tissue-type incompatibility (cf. Zenios, Woodle, and Ross, 2001).

If we eliminate these assumptions, the structure of the dynamic programming problem will change. Even then, we can create object types and their compatibility relation as a general partial order. Hence, we can classify the pair types as underdemanded, overdemanded, self-demanded, and reciprocally demanded. Using results in dynamic programming, it can be shown that an efficient deterministic Markov mechanism exists.

5.2.2. Computational approximation for the efficient kidney exchange mechanism.

The threshold values of the efficient multi-way kidney exchange mechanism cannot be solved analytically. In this section, using different parameters for $\frac{\lambda}{\lambda+\rho}$ and using $p_c, \{q_{X-Y}\}_{X-Y \in \mathcal{P}}$ values reported in the medical literature, we numerically compute the efficient matching mechanism's threshold values under Assumptions 1, 2, 3, and 4. Then we use these threshold values to approximate the thresholds when Assumption 3 does not hold and self-demanded types can participate in exchange (see Remark 1 in Appendix B), for subsequent policy simulations.

The algorithm used to compute the efficient threshold values uses Theorem 2 and the value iteration formula in Theorem 4 in Appendix A (see Puterman, 1994, p. 259 for a one-sided threshold version of the algorithm). The algorithm makes a 6001 state approximation (3000 negative and 3000 positive states, and state 0) of the infinite countable state space. The cross-match probability is reported as $p_c = 0.11$ by Zenios, Woodle and Ross (2001). We also use this number. The medical literature is not precise about the arrival probabilities of the pairs. We have chosen the following way to construct these probabilities. The blood type frequencies of people are widely reported for the US population as follows: For O blood type $q_O = 0.45$, for A blood type $q_A = 0.40$, for B blood type $q_B = 0.11$, and for AB blood type $q_{AB} = 0.04$.²² We assume that the pairs are blood-type unrelated (such as spouses), and hence the donor and recipient blood types are independently distributed. That is, for any $X-Y \in \mathcal{P}$, we have $q_{X-Y} = q_X q_Y$.

We also compute the mechanism when q_{A-B} and q_{B-A} are not equal to each other. Terasaki, Gjertson and Cecka (1998) report that A-B and B-A blood type pairs do not arrive at the same frequency. They report that $q_{A-B} = 0.05$ and $q_{B-A} = 0.03$. In our computation, additionally, we use two different probability pairs: (1) $q_{A-B} = 0.049$ and $q_{B-A} = 0.039$ and (2) $q_{A-B} = 0.054$ and $q_{B-A} = 0.034$.

Since we assume in our initial efficient mechanism derivation that self-demanded types are not included, we find the conditional probabilities using the above formula such that arriving pairs are not self-demanded.

Since we do not have a clear prediction of the values of ρ and λ , we use different values in the computation. In particular, we choose different values for $\frac{\lambda}{\lambda+\rho}$ and derive the efficient mechanism. The set of values we use for $\frac{\lambda}{\lambda+\rho}$ is given as²³

$$\{0.999995, 0.99999, 0.99995, 0.9999, 0.9995, 0.999, 0.995, 0.99, 0.95\}.$$

First, note that in all cases $\underline{s}^* \leq 0$ and $\bar{s}^* = 0$. We report the threshold value for the stock of B-A type pairs to conduct the smaller exchanges, $|\underline{s}^*|$ in Table 1. For the number of B-A type pairs in the pool larger than $|\underline{s}^*|$, the efficient mechanism requires the largest exchanges.

We observe that, under the most plausible $\frac{\lambda}{\lambda+\rho}$ values,

$$\{0.999995, 0.99999, 0.99999, 0.99995, 0.9999, 0.9995, 0.999\},$$

the efficient mechanism requires a positive stock of B-A blood type pairs before conducting the largest possible exchanges. Only an unrealistic value such as $\frac{\lambda}{\lambda+\rho} = 0.995$ and lower

22. For example, see the webpage of the Association of American Blood Banks, <http://www.aabb.org>, retrieved on 27 February 2007.

23. For example, $\frac{\lambda}{\lambda+\rho} = 0.999995$ can be generated by $\lambda = 10,000$ and $\rho = 0.05$, which corresponds to 10,000 pairs arriving per year and an annual discount rate of 5%. On the other hand, $\frac{\lambda}{\lambda+\rho} = 0.9999$ can be generated by $\lambda = 10,000$ and $\rho = 0.10$. We can roughly assume that the discount rate is 5–10%. Expectations for λ nationwide is around 10,000, given that the annual number of conducted live kidney donations is in the 6000–7000 range in the last few years. The lower values for $\frac{\lambda}{\lambda+\rho}$ can also be expected in regional smaller programmes. For example, $\frac{\lambda}{\lambda+\rho} = 0.999$ can be generated through $\lambda = 50$ and $\rho = 0.05$.

TABLE 1
The threshold number of B–A type pairs for conducting smaller exchanges in the optimal rule

| \underline{s}^* | $\frac{\lambda}{\lambda+\rho}$ | | | | | | | | |
|-----------------------------------------|--------------------------------|---------|---------|--------|--------|-------|-------|------|------|
| | 0.999995 | 0.99999 | 0.99995 | 0.9999 | 0.9995 | 0.999 | 0.995 | 0.99 | 0.95 |
| $q_{B-A} = q_{A-B} = 0.044$ | 2 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 0 |
| $q_{B-A} = 0.039$ and $q_{A-B} = 0.049$ | 292 | 161 | 46 | 28 | 9 | 6 | 2 | 1 | 0 |
| $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$ | 2773 | 1387 | 278 | 147 | 30 | 15 | 3 | 2 | 0 |

(requiring only 10 pairs arriving per year at 5% discounting for ρ) may require conducting the largest possible exchanges all the time. We also observe that the threshold value increases with increasing $(q_{A-B} - q_{B-A})$ and increasing $\frac{\lambda}{\lambda+\rho}$. For example, when $\frac{\lambda}{\lambda+\rho} = 0.999995$ (with an average of 10,000 compatible and incompatible pairs arriving per year and an annual discount rate $\rho = 5\%$), $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$, the largest exchanges involving B–A type pairs will be conducted if and only if there are more than 2773 B–A type pairs in the pool.

5.2.3. Simulations on expected exchange surplus. In this subsection, we relax Assumption 3 again, and assume that self-demanded types can participate in exchange. We compute the expected 1-year exchange surplus (normalized by the two-way exchange regime) at null state (having no A–B or B–A type pairs, and no self-demanded type pairs) for two different matching mechanisms. We use

- **Regime 1:** The single-state variable, one-threshold approximation of the dynamically efficient multi-way matching mechanism, $\hat{\phi}^{\bar{s}^*, \underline{s}^*}$ (cf. Appendix B).
- **Regime 2:** Dynamically efficient two-way matching mechanism v .

We used the following technique in our simulation. We roughly calibrated our parameters using the US data. We chose $\lambda = 10,000$ (given that 6570 live donor transplants are conducted per year, and assumed that 10,000 pairs arrive per year) and $\rho = 0.05$ (that is, the discount rate is 5%) with $\frac{\lambda}{\lambda+\rho} = 0.999995$. We set $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$, as reported by Terasaki, Gjertson and Cecka (1998). We assumed that there were arbitrarily many underdemanded pairs (Assumption 1) and that there was no tissue-type incompatibility between two different pairs (Assumption 4). We simulated the pool for the next arriving 10,000 pairs (approximately for 1 year) and calculated the normalized surplus raised taking the two-way exchange as numéraire. We ran this simulation 5000 times. The averages and standard errors of the averages for the 1-year normalized exchange surplus were taken over these 5000 markets (see Table 2). We observed that the efficient multi-way exchange raises about 6.6% more expected surplus than the efficient two-way exchange. This difference is significant at the 1% level using a z-test.

We report the number of pairs matched in 1 year under the two different regimes. We also report the number of pairs that could have been matched if all exchanges were run at the end of the year in a static population. Under the efficient multi-way mechanism, about 6.7% more pairs are matched than the efficient two-way mechanism. This difference is significant at the 1% level using a z-test. Even though the efficient exchange is conducted dynamically, the numbers of pairs matched is close to the maximal possible number (see Table 3). This is an expected result. By Proposition 1, we know that the efficient two-way matching mechanism matches the maximum number of pairs possible, and this table shows that. On the other hand, under the efficient multi-way mechanism, this observation may not be true, since some B–A

TABLE 2

Policy simulations for 1-year normalized exchange surplus taking two-way regime numéraire starting from the null state under the two regimes, Regime 1: the one-threshold approximation of the optimal rule, Regime 2: the optimal two-way matching rule

| | $\lambda = 10,000$ and $\rho = 0.05$ |
|-----------------------------------------------------------|-----------------------------------------|
| One-year exchange surplus taking two-way regime numéraire | $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$ |
| Regime 1: Multi-way | 106.59 (0.0004694) |
| Regime 2: Two-way | 100 (0.0004325) |

TABLE 3

Policy simulations for number of pairs matched in exchanges starting from the null state under the two regimes. With $\lambda = 10,000$, on average 4267 pairs enter the exchange. On average, 6733 pairs are compatible and their recipients receive a transplant immediately from their own donors

| | $\lambda = 10,000$ and $\rho = 0.05$ |
|-----------------------------------|-----------------------------------------|
| Number of pairs matched in 1 year | $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$ |
| Regime 1: Multi-way | 1791.51 (0.79) |
| Regime 2: Two-way | 1680.77 (0.73) |
| Static: Multi-way | 1794.39 (0.80) |
| Static: Two-Way | 1680.77 (0.73) |

TABLE 4

Average number of exchanges of different sizes in Regime 1

| | $\lambda = 10,000$ and $\rho = 0.05$ |
|-----------------------------------------------|-----------------------------------------|
| Number of exchanges in Regime 1: Unrestricted | $q_{B-A} = 0.034$ and $q_{A-B} = 0.054$ |
| 2-way | 492.62 (0.32) |
| 3-way | 180.51 (0.17) |
| 4-way | 49.04 (0.096) |
| 5-way | 11.36 (0.047) |
| 6-way | 1.83 (0.019) |
| 7-way | 0.11 (0.0047) |
| 8-way | 0.0016 (0.00056) |

or A–B type pairs may remain in the pool at the end of the year, and those could have been matched in a static exchange run at the end of the year.²⁴

We also report the number of exchanges of different sizes under Regime 1: Efficient multi-way exchange in Table 4 (in approximately 1 year). These are the average numbers found in the above simulation. We observe that the majority of the exchanges are two-way exchanges, though we observe a substantial number of three-way and four-way exchanges. The numbers of larger exchanges are substantially less (less than 2% of all exchanges). We observe that 67% of all exchanges conducted are two-way, 25% are three-way, and only 7% are four-way exchanges. Therefore, the efficient multi-way mechanism does not create a large burden in terms of large exchanges.

24. Note that this is only an artifact of our simulation environment, which is terminated after 1 year. Since the time horizon in reality is infinite, surely these remaining pairs will be matched in the next year.

6. CONCLUSIONS

Having a partial order compatibility structure (which is not a linear order) is the necessary requirement for multi-way dynamically efficient mechanisms having state-dependent features and being different from statically efficient mechanisms. We use a minimal partial order structure to derive dynamically efficient exchange mechanisms in a general exchange model.

We observe three important properties of dynamically efficient mechanisms. They (for both two-way and multi-way matching) are not affected by the magnitude of the unit waiting cost c . They conduct at most one exchange at a time. Moreover, whenever an exchange becomes feasible, they conduct it immediately.

In a static setting, Roth, Sönmez and Ünver (2007) showed that n -way exchanges usually suffice to obtain all benefits from an exchange domain with n object types under a partial order compatibility relation and mild assumptions. In our study, for kidney exchanges, when self-demanded type pairs participate in exchange, the largest possible exchange size is 8 instead of 4 as predicted by the above result, since in a dynamic setting some of the assumptions of the above study do not hold. In the simulations conducted, we showed that exchanges larger than four-way are extremely rare in a dynamic setting.

The policy simulations show that the threshold values of the efficient kidney exchange mechanism are quite sensitive to the changes in arrival probabilities of A–B and B–A type pairs. Therefore, for our mechanism to have a realistic application, the health authority should measure these arrival rates, precisely, and these rates should be close to each other.

A final note about incentive properties of dynamically efficient mechanisms will be useful. We can refine the definition of efficient mechanisms as follows. If an X–Y type pair is going to be matched in an exchange and there are multiple X–Y type pairs available in the pool, then the mechanism selects the earliest arriving pair. Suppose that a pair of type X–Y $\in \mathcal{P}$ can manipulate its type and announce it as W–Z $\in \mathcal{P}$ with $W \blacktriangleright X$ and $Y \blacktriangleright Z$.²⁵ It is easy to show that announcing X–Y is the weakly dominant strategy for the pair, i.e. the mechanisms are *strategy-proof*.²⁶ Entry timing can be another strategic tool. Suppose that each pair, after becoming available, can delay its entry to the pool as a strategic variable. In this case, the above dynamically efficient two-way and multi-way matching mechanisms are *delay-proof*, i.e. no pair will benefit by delaying its entry to the pool.

APPENDIX A. PROOFS OF RESULTS

Proof of Proposition 2. Suppose that pair i of type X–Y $\in \mathcal{P}^O$ is the only overdemanded pair in the pool, $j \neq i$ is a type Z_1 – $Z_2 \in \mathcal{P}$ pair in the pool, and $E = (j, j_1, \dots, j_k)$ is an exchange that matches pair j . Let A^ℓ – O^ℓ be the type of each pair $j_\ell \in E$. We have $Z_2 \blacktriangleright A^1, O^\ell \blacktriangleright A^{\ell+1}$ for all $\ell \in \{1, \dots, k-1\}$, and $A^k \blacktriangleright Z_1$. Two cases are possible:

- Type of $j \in \mathcal{P}^{U\ell}$: Since $Z_1 \blacktriangleright Z_2$ and $Z_2 \neq Z_1$, by acyclicity of \blacktriangleright , there exists one pair j_ℓ with $O^\ell \blacktriangleright A^\ell$ and $O^\ell \neq A^\ell$, i.e. there exists an overdemanded pair $j_\ell \in E$. Since i is the single overdemanded pair in the pool, $j_\ell = i$. By transitivity of \blacktriangleright and by the fact that there are at most two object types at a compatibility level of \blacktriangleright , we have (1a) $Z_2 \blacktriangleright X$ or (1b) $Z_2 \blacktriangleright X$ and $X \blacktriangleright Z_2$, and yet there exists some $j_m \in E$ with $m < \ell$ such that j_m is of type Z_2 – X (so that E is individually rational). Similarly, we have (2a) $Y \blacktriangleright Z_1$ or (2b) $Z_1 \blacktriangleright Y$

25. Observe that announcing $Y \blacktriangleright Z$ or $W \blacktriangleright X$ may result with individually irrational exchanges. Hence, we assume that such manipulations are not possible.

26. In the context of kidney exchange, since blood types exclusively determine the compatibility between a recipient and a donor of another pair, and since manipulating blood types is extremely difficult, it is almost impossible for a pair to use “compatibility” as a strategic tool to manipulate the dynamic system.

and $Y \blacktriangleright Z_1$, and yet there exists some $j_m \in E$ with $m > \ell$ such that j_m is of type $Y-Z_1$.²⁷ This proves necessity.

- If (1a) and (2a) are satisfied, we can always choose E (in terms of types of pairs) as $(Z_1-Z_2, X-Y)$.
- If (1b) and (2a) are satisfied, we can choose E as $(Z_1-Z_2, Z_2-X, X-Y)$.
- If (1a) and (2b) are satisfied, we can choose E as $(Z_1-Z_2, X-Y, Y-Z_1)$.
- If (1b) and (2b) are satisfied, we can choose E as $(Z_1-Z_2, Z_2-X, X-Y, Y-Z_1)$.

These prove sufficiency.

- Type of $j \in \mathcal{P}^S$: Since $Z_2 = Z_1$, when there is another pair h of type Z_1-Z_1 , a two-way exchange consisting of types (Z_1-Z_1, Z_1-Z_1) is an individually rational exchange, and E could be chosen using these types. Suppose that there is no other pair of type Z_1-Z_1 in the pool. Then by acyclicity of \blacktriangleright , there exists some pair j_ℓ with $O^\ell \blacktriangleright A^\ell$ with $O^\ell \neq A^\ell$, i.e. there exists an overdemanded pair $j_\ell \in E$. Since i is the single overdemanded pair in the pool, $j_\ell = i$. By transitivity of \blacktriangleright and by the fact that there are at most two object types at a compatibility level of \blacktriangleright , we have (1a) $Z_1 \blacktriangleright X$ or (1b) $Z_1 \blacktriangleright X$ and $X \blacktriangleright Z_1$, and yet there exists some $j_m \in E$ with $m < \ell$ such that j_m is of type Z_1-X (so that E is individually rational). Similarly, we have (2a) $Y \blacktriangleright Z_1$ or (2b) $Z_1 \blacktriangleright Y$ and $Y \blacktriangleright Z_1$, and yet there exists some $j_m \in E$ with $m > \ell$ such that j_m is of type $Y-Z_1$. These prove necessity.

- If (1a) and (2a) are satisfied, we can always choose E (in terms of types of pairs) as $(Z_1-Z_1, X-Y)$.
- If (1b) and (2a) are satisfied, we can choose E as $(Z_1-Z_1, Z_1-X, X-Y)$.
- If (1a) and (2b) are satisfied, we can choose E as $(Z_1-Z_1, X-Y, Y-Z_1)$.
- If (1b) and (2b) are satisfied, we can choose E as $(Z_1-Z_1, Z_1-X, X-Y, Y-Z_1)$.

These prove sufficiency.

- Type of $j \in \mathcal{P}^R$: We have $Z_2 \blacktriangleright Z_1$ and $Z_1 \blacktriangleright Z_2$. Suppose there is a pair h of type Z_2-Z_1 . Then a two-way exchange consisting of types (Z_1-Z_2, Z_2-Z_1) is an individually rational exchange, and E could be chosen using these types. Suppose that there is no pair of type Z_2-Z_1 in the pool. Then by acyclicity of \blacktriangleright , there exists some pair j_ℓ with $O^\ell \blacktriangleright A^\ell$ with $O^\ell \neq A^\ell$, i.e. there exists an overdemanded pair $j_\ell \in E$. Since i is the single overdemanded pair in the pool, $j_\ell = i$. By the fact that there are only two types in the compatibility levels of Z_1 and Z_2 , there are no possible reciprocal types other than Z_1-Z_2 and Z_2-Z_1 . Since Z_2-Z_1 type pair does not exist, there is no other pair of the same compatibility level with in Z_1-Z_2 in the exchange E , and by acyclicity we have $Z_2 \blacktriangleright X$ and $Y \blacktriangleright Z_1$ i.e. $Z-Y$ and Z_1-Z_2 are mutually compatible types, proving necessity. The types of pairs in E can be chosen as $(Z_1-Z_2, X-Y)$ whenever $Z_2 \blacktriangleright X$ and $Y \blacktriangleright Z_1$, proving sufficiency. \parallel

Proposition 6 (Maximal exchange composition using overdemanded types). *Under Assumption 1, suppose that $X-Y \in \mathcal{P}^O$ is the type of an overdemanded pair that arrives at the exchange pool. Then, we can conduct an $(n + k + \ell + 1)$ -way exchange serving*

- the overdemanded pair of type $X-Y$;
- a maximum of $n = L_X - L_Y$ underdemanded pairs;
- one pair from each of the distinct reciprocally demanded types $W_1-W_2, W_3-W_4, \dots, W_{2k-1}-W_{2k} \in \mathcal{P}^R$ such that $W_1, W_2 \blacktriangleright W_3, W_4 \blacktriangleright \dots \blacktriangleright W_{2k-1}, W_{2k}$ (i.e. these pair types are not reciprocal of another and are ordered according to their compatibility levels), $Y \blacktriangleright W_1$ and $W_{2k} \blacktriangleright X$.
- one pair from each of the distinct self-demanded types $V_1-V_1, \dots, V_\ell-V_\ell \in \mathcal{P}^S$ such that (1) $V_1 \blacktriangleleft V_2 \blacktriangleleft \dots \blacktriangleleft V_\ell$, (2) $Y \blacktriangleright V_1$ or $W_1-W_2 = Y-V_1$, (3) $V_\ell \blacktriangleright X$ or $W_{2k-1}-W_{2k} = V_\ell-X$, and (4) if there exists some $d \in \{1, \dots, \ell - 1\}$ such that V_d and V_{d+1} are at the same level then there exists some index $c_d \in \{1, \dots, k\}$ such that $W_{2c_d-1}-W_{2c_d} = V_d-V_{d+1}$;

whenever such reciprocally demanded and self-demanded pairs exist in the pool.

Proof of Proposition 6. Suppose the hypothesis of the proposition holds. For notational purposes, let $Z_{-1} = X$, $Z_0 = Y$, $Z_{2n+1} = X$, and $Z_{2n+2} = Y$. Under Assumption 1, there exists n underdemanded pairs belonging to pair types

$$Z_1-Z_2, Z_3-Z_4, \dots, Z_{2n-1}-Z_{2n} \in \mathcal{P}^U$$

27. Equivalently, we could have written Condition (1) as “ $X \blacktriangleright Z_2$ and if $Z_2 \blacktriangleright X$ then there exists some $j_m \in E$ with $m < \ell$ such that j_m is of type Z_2-X ” as in the hypothesis of the proposition. A similar equivalence is also valid for Condition (2). Thus, these are equivalent to the conditions given in the hypothesis of the proposition.

such that

- for each $m \in \{1, 2, \dots, n\}$, there are m levels between Z_{2m} and Y , that is $L_{Z_{2m}} = L_Y + m$;
- for each $c \in \{1, 2, \dots, k\}$, there exists an index $m_c \in \{1, 2, \dots, n\}$ such that $Z_{2m_c} = W_{2c-1}$ and $Z_{2m_c+1} = W_{2c}$;
- for each $d \in \{1, 2, \dots, \ell\}$ with $V_{d-1} \blacktriangleright V_d$ (whenever V_{d-1} exists) and $V_d \blacktriangleright V_{d+1}$ (whenever V_{d+1} exists), there exists an index $m'_d \in \{1, 2, \dots, k\}$ such that $Z_{2m'_d} = V_d$; and
- for each $m \in \{1, 2, \dots, n-1\} \setminus \{m_1, \dots, m_k\}$, $Z_{2m} = Z_{2m+1}$.

Thus, the exchange E' consisting of pairs belonging to pair types

$$\left(X-Y, \underbrace{Z_1 - Z_2}_{=Y}, \underbrace{Z_3 - Z_4}_{=Z_2}, \dots, \underbrace{Z_{2m_{c-1}} - Z_{2m_c}}_{=W_{2c-1}}, W_{2c-1} - W_{2c}, \underbrace{Z_{2m_{c+1}} - Z_{2m_{c+2}}}_{=W_{2c}}, \dots, \underbrace{Z_{2n-1} - Z_{2n}}_{=Z_{2n-2}} - X \right)$$

for all $c = 1, 2, \dots, k$.

is a feasible $(k + n + 1)$ -way exchange.

We can enlarge exchange E' by inserting the given self-demanded type pairs in order to obtain exchange E'' as follows:

- Recall that for each $d \in \{1, \dots, \ell-1\}$ with same level V_{d+1} and V_d , there exists some index $c_d \in \{1, \dots, k\}$ such that $W_{2c_d-1} - W_{2c_d} = V_d - V_{d+1}$. In the exchange E' above, we can insert

- the $V_d - V_d$ type pair between the $Z_{2m_{c_d-1}} - \underbrace{Z_{2m_{c_d}}}_{=W_{2c_d-1}}$ type pair, and $W_{2c_d-1} - W_{2c_d}$ type reciprocally demanded pair; and
- the $V_{d+1} - V_{d+1}$ type pair between the $W_{2c_d-1} - W_{2c_d}$ type reciprocally demanded pair and the $\underbrace{Z_{2m_{c_d}+1} - Z_{2m_{c_d}+2}}_{=W_{2c_d}}$ type pair.

- For each $d \in \{1, \dots, \ell\}$ with $V_{d-1} \blacktriangleright V_d$ (whenever V_{d-1} exists) and $V_d \blacktriangleright V_{d+1}$ (whenever V_{d+1} exists), since the object type $Z_{2m'_d}$ is chosen as $Z_{2m'_d} = V_d$, we can insert the $V_d - V_d$ type self-demanded pair, in exchange E' , between the pairs $Z_{2m'_{d-1}} - Z_{2m'_d}$ and $\underbrace{Z_{2m'_d+1} - Z_{2m'_d+2}}_{=Z_{2m'_d}}$.

Thus, the newly formed exchange E'' serves all of the $n + k + \ell + 1$ pairs including the ones given in the hypothesis of the proposition. \parallel

Proof of Proposition 3. Suppose Assumption 1 holds. Let an overdemanded pair i of type $X-Y \in \mathcal{P}^O$ arrive at the exchange pool. We will show that the opportunity cost of holding onto the $X-Y$ type pair and underdemanded pairs, which could be matched immediately, with the expectation of creating a larger exchange in the future is larger than any alternative decision.

First note that pair i will not be used in matching an underdemanded pair that will arrive in the future. Since all underdemanded pairs exist abundantly by Assumption 1, by Corollary 1 we can use it to match $L_X - L_Y$ underdemanded pairs in an exchange E immediately. Moreover suppose that we can match in total n pairs in this exchange (possibly including some reciprocally demanded and self-demanded pairs). In the future, $L_X - L_Y$ is the most underdemanded pairs we can match through pair i , thus we do not hold onto i to match future underdemanded pairs.

We will show that pair i will not be used in matching a self-demanded type pair that will arrive in the future, either. Suppose that $V-V$ is a self-demanded type and a pair of this type can be inserted in exchange E (see Proposition 6 and its proof). Hence, if pair i is used to wait for a $V-V$ type pair to arrive, n pairs in exchange E will wait until the $V-V$ type pair arrives, instead of being matched immediately. A $V-V$ type pair can be matched in several ways. It can be matched with another $V-V$ type pair in a two-way exchange. Or it can be inserted in other exchanges between two pairs such that the object of the first pair is compatible with V and the requirement of the agent of the second pair is also compatible with V . Consider the case in which we match it exclusively with a future $V-V$ type pair j . For the same expected duration that pairs in exchange E wait for pair j to arrive, pair j will wait until the next $V-V$ type pair arrives. Thus, the cost of this exchange is making a future $V-V$ type pair j wait for the same expected duration for a new $V-V$ type pair. This second alternative is less costly than making n (which is larger than 1) pairs

of the exchange E wait for the same expected duration; therefore an X - Y type pair i will not be used to match an expected V - V type pair in the future.

Next, we show that pair i will not be used in matching a reciprocally demanded type pair that will arrive in the future. Suppose that instead of exchange E , we use the type X - Y pair to match one reciprocally demanded pair k of type W_1 - W_2 that will arrive in the future. Moreover, by Proposition 2, pairs in E (other than pair i) cannot be matched without i . Thus, suppose that we would like to use pair i to serve also this first pair k which will arrive in the future. This causes the exchange E not to be conducted immediately and forces n pairs to wait. By Corollary 1, we can match $n + 1$ pairs (including k) immediately when k arrives, if we do not conduct exchange E now.

We will find an upper-bound for exchange surplus regarding these n pairs and all W_1 - W_2 and W_2 - W_1 type pairs that will arrive in the future. Then, we will find a lower-bound for exchange surplus when n pairs are instantly matched within exchange E and the overdemanded type pair i is not held on to. Then, we will show that when $p_{W_1-W_2}$ and $p_{W_2-W_1}$ are sufficiently close to each other, the second surplus is greater than the first one.

Observe that the expected time difference between arrival of W_1 - W_2 type pairs, τ_1 , follows an exponential distribution with density function $\lambda p_{W_1-W_2} e^{-\lambda p_{W_1-W_2} \tau_1}$, and the expected discounting between those two arrivals is $E[e^{-\rho \tau_1}] = \int_0^\infty e^{-\rho \tau_1} \lambda p_{W_1-W_2} e^{-\lambda p_{W_1-W_2} \tau_1} d\tau_1 = \frac{\lambda p_{W_1-W_2}}{\lambda p_{W_1-W_2} + \rho}$. Similarly, the expected discounting until a W_2 - W_1 type arriving is $\frac{\lambda p_{W_2-W_1}}{\lambda p_{W_2-W_1} + \rho}$, and a W_1 - W_2 or W_2 - W_1 type arriving is $\frac{\lambda(p_{W_1-W_2} + p_{W_2-W_1})}{\lambda(p_{W_1-W_2} + p_{W_2-W_1}) + \rho}$ (since the arrival of a W_1 - W_2 or W_2 - W_1 type pair is a Poisson with rate $\lambda p_{W_1-W_2} + \lambda p_{W_2-W_1}$). For simplicity of notation, until the end of the proof, we use

$$\lambda_1 \equiv \lambda p_{W_1-W_2} \quad \text{and} \quad \lambda_2 \equiv \lambda p_{W_2-W_1}.$$

Also observe that the upper-bound of total expected surplus assuming that all W_1 - W_2 type pairs are matched as soon as they arrive is given as:

$$\left(\frac{\lambda_1}{\lambda_1 + \rho}\right) \frac{c}{\rho} + \left(\frac{\lambda_1}{\lambda_1 + \rho}\right)^2 \frac{c}{\rho} + \dots + \left(\frac{\lambda_1}{\lambda_1 + \rho}\right)^m \frac{c}{\rho} + \dots = \frac{\lambda_1 c}{\rho}.$$

Similarly, the upper-bound of total expected surplus assuming that all W_2 - W_1 type pairs are matched as soon as they arrive is given as $\frac{\lambda_2 c}{\rho}$.

- First, we find an upper-bound of surplus (regarding pairs in E and all future W_1 - W_2 and W_2 - W_1 type pairs) from waiting and not conducting exchange E immediately:

$$\begin{aligned} \frac{\rho}{c} ES^1 &= \frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \rho} \left[\frac{\lambda_1}{\lambda_1 + \lambda_2} \left\{ (n + 1) + \frac{\lambda_1}{\rho} + \frac{\lambda_2}{\rho} \right\} + \frac{\lambda_2}{\lambda_1 + \lambda_2} \left\{ n + 1 + \frac{\lambda_2}{\rho} + \frac{\lambda_1}{\rho} \right\} \right] \\ &= \frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \rho} \left[(n + 1) + \frac{\lambda_1}{\rho} + \frac{\lambda_2}{\rho} \right] \end{aligned}$$

where in the first line $\frac{\lambda_1 + \lambda_2}{\lambda_1 + \lambda_2 + \rho}$ is the discounting that occurs until either a W_1 - W_2 or W_2 - W_1 pair arrives and

- probability $\frac{\lambda_1}{\lambda_1 + \lambda_2}$ refers to the pair arriving being of type W_1 - W_2 and normalized (by $\frac{c}{\rho}$) surplus $n + 1$ refers to the fact that we conduct the $(n + 1)$ -way exchange using the W_1 - W_2 type pair and the waiting n pairs, normalized surplus $\frac{\lambda_1}{\rho} + \frac{\lambda_2}{\rho}$ is an upper-bound of all future matches regarding W_1 - W_2 and W_2 - W_1 type pairs;
- probability $\frac{\lambda_2}{\lambda_1 + \lambda_2}$ refers to the pair arriving being of type W_2 - W_1 and normalized surplus n refers to the fact that we conduct exchange E at that instance, and $1 + \frac{\lambda_1}{\rho} + \frac{\lambda_2}{\rho}$ is the surplus of matching the W_2 - W_1 pair immediately (an upper-bound assumption) and all other future W_1 - W_2 and W_2 - W_1 type pairs as soon as they arrive (another upper-bound assumption).²⁸
- Second, we find a lower-bound for the efficient surplus (regarding pairs in E and all future W_1 - W_2 and W_2 - W_1 type pairs) when we conduct exchange E immediately:

$$\frac{\rho}{c} ES^2 = n + 2 \frac{\min\{\lambda_1, \lambda_2\}}{\rho}$$

28. This is not a tight upper-bound and smaller upper-bounds can be found.

where n refers to the normalized immediate exchange surplus regarding n pairs in conducted exchange E and $2 \frac{\min\{\lambda_1, \lambda_2\}}{\rho}$ refers to the lower-bound of surplus found by matching W_1 - W_2 type pairs exclusively with W_2 - W_1 type pairs in the future.²⁹

We observe that when λ_1 is sufficiently close to λ_2 , $\frac{\rho}{c} \underline{ES}^2 > \frac{\rho}{c} \overline{ES}^1$. Thus, overdemanded pair i will be immediately matched in n -way exchange E for efficient matching.³⁰ ||

Theorem 4 (The Existence and Uniqueness Theorem). *Let Z be a countable state set. Let F be a finite action set. Let \mathcal{V} be the set of bounded functions defined from Z to \mathbb{R} . Let $0 \leq \delta < 1$. For any $z \in Z$, let*

$$v(z) = \delta \max_{f \in F} \left\{ r(z, f) + \sum_{\sigma \in Z} p(\sigma | z, f) v(\sigma) \right\}, \tag{A1}$$

where (i) for all $\sigma \in Z$ and all $f \in F$, $p(\sigma | z, f) \geq 0$, and for all $f \in F$, $\sum_{\sigma \in Z} p(\sigma | z, f) = 1$, and (ii) for all $f \in F$, $r(z, f) \in \mathbb{R}$ is bounded. Then:

1. Function $v \in \mathcal{V}$ exists and is uniquely defined as the limit of the sequence $\{v^m\} \subseteq \mathcal{V}$ (under the sup norm),³¹ where v^0 is arbitrary, and for any $m > 0$,

$$v^m(z) = \delta \max_{f \in F} \left\{ r(z, f) + \sum_{\sigma \in Z} p(\sigma | z, f) v^{m-1}(\sigma) \right\}. \tag{A2}$$

2. There exists a (deterministic) Markovian mechanism $\phi : Z \rightarrow F$ such that for all $z \in Z$,

$$v(z) = \delta \left\{ r(z, \phi(z)) + \sum_{\sigma \in Z} p(\sigma | z, \phi(z)) v(\sigma) \right\}. \tag{A3}$$

We will use the above theorem in our proof of Proposition 4.

Proof of Proposition 4. Let W_1 - $W_2 \in \mathcal{P}^{\mathbb{R}^*}$. Let $F = \{\text{do-not-match}, \text{match}\}$ and $f_1 = \text{do-not-match}$, $f_2 = \text{match}$. Consider the Bellman equations given in equations (17), (18), and (19). Let the normalized surplus for choosing the smaller exchanges (action f_1) regarding W_1 - W_2 be given by

$$r(s_{W_1-W_2}, f_1) = \begin{cases} 2p_{W_2-W_1} & \text{if } s_{W_1-W_2} > 0 \\ 0 & \text{if } s_{W_1-W_2} = 0 \\ 2p_{W_1-W_2} & \text{if } s_{W_1-W_2} < 0 \end{cases}, \tag{A4}$$

and the normalized surplus for choosing larger exchanges (action f_2) be given by

$$r(s_{W_1-W_2}, f_2) = \begin{cases} 2p_{W_2-W_1} + \sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} & \text{if } s_{W_1-W_2} > 0 \\ 0 & \text{if } s_{W_1-W_2} = 0 \\ 2p_{W_1-W_2} + \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y} & \text{if } s_{W_1-W_2} < 0 \end{cases}. \tag{A5}$$

When smaller exchanges (action f_1) are chosen, the transition probabilities are given by

$$\begin{aligned} p(s_{W_1-W_2} - 1 | s_{W_1-W_2}, f_1) &= p_{W_2-W_1}, \\ p(s_{W_1-W_2} | s_{W_1-W_2}, f_1) &= 1 - p_{W_1-W_2} - p_{W_2-W_1}, \\ p(s_{W_1-W_2} + 1 | s_{W_1-W_2}, f_1) &= p_{W_1-W_2}. \end{aligned} \tag{A6}$$

29. This is not a tight lower-bound, and bigger lower-bounds can be found.

30. The situations in which pair i can be used in matching multiple reciprocal type pairs in different levels is very similar to this case and skipped for brevity.

31. For all $v \in \mathcal{V}$, $\|v\| = \sup_{s \in S} |v(s)|$ is the sup norm of v .

When larger exchanges (action f_2) are chosen, the transition probabilities are given by

$$\begin{aligned}
 p(s_{W_1-W_2} - 1 \mid s_{W_1-W_2}, f_2) &= \begin{cases} p_{W_2-W_1} + \sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} & \text{if } s_{W_1-W_2} > 0 \\ p_{W_2-W_1} & \text{if } s_{W_1-W_2} \leq 0 \end{cases}, \\
 p(s_{W_1-W_2} \mid s_{W_1-W_2}, f_2) &= \begin{cases} 1 - p_{W_1-W_2} - p_{W_2-W_1} - \sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} & \text{if } s_{W_1-W_2} > 0 \\ 1 - p_{W_1-W_2} - p_{W_2-W_1} & \text{if } s_{W_1-W_2} = 0 \\ 1 - p_{W_1-W_2} - p_{W_2-W_1} - \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y} & \text{if } s_{W_1-W_2} < 0 \end{cases}, \quad (A7) \\
 p(s_{W_1-W_2} + 1 \mid s_{W_1-W_2}, f_2) &= \begin{cases} p_{W_1-W_2} & \text{if } s_{W_1-W_2} \geq 0 \\ p_{W_1-W_2} + \sum_{X-Y \in \mathcal{P}^O(W_2-W_1)} p_{X-Y} & \text{if } s_{W_1-W_2} < 0 \end{cases}.
 \end{aligned}$$

Let $\mathcal{V} = \{v : \mathbb{Z} \rightarrow \mathbb{R}_+ \text{ such that } v \text{ is bounded}\}$ be the set of Markov surplus functions for W_1-W_2 types. Let $v^0 \in \mathcal{V}$. For all $m \in \{1, 2, 3, \dots\} (\equiv \mathbb{Z}_{++})$, let $v^m \in \mathcal{V}$ be defined through the following recursive system,

$$v^m(s_{W_1-W_2}) = \max_{f \in \{f_1, f_2\}} w^m(s_{W_1-W_2}, f) \tag{A8}$$

with $w^m : \mathbb{Z} \times \{f_1, f_2\} \rightarrow \mathbb{R}_+$ defined for all $f \in \{f_1, f_2\}$ as follows:

$$w^m(s_{W_1-W_2}, f) = \frac{\lambda}{\lambda + \rho} [r(s_{W_1-W_2}, f) + \sum_{\sigma=s_{W_1-W_2}-1}^{s_{W_1-W_2}+1} (p(\sigma \mid s_{W_1-W_2}, f) v^{m-1}(\sigma))]. \tag{A9}$$

The state component space for W_1-W_2 and W_2-W_1 types, \mathbb{Z} , is countable. Action space $F = \{f_1, f_2\}$ is finite. Since $\lambda > 0$ and $\rho > 0$, we have $0 < \frac{\lambda}{\lambda + \rho} < 1$. Observe that by equations (A6) and (A7), for any $s_{W_1-W_2} \in \mathbb{Z}$ and $f \in F$, $p(\sigma \mid s_{W_1-W_2}, f) \geq 0$ for all $\sigma \in \mathbb{Z}$, and, $\sum_{\sigma=s_{W_1-W_2}-1}^{s_{W_1-W_2}} p(\sigma \mid s_{W_1-W_2}, f) = 1$. By equations (A4) and (A5), for any $s_{W_1-W_2} \in \mathbb{Z}$ and $f \in F$, $r(s_{W_1-W_2}, f)$ is bounded. Since equations (A4)–(A9) are directly obtained from the Bellman equations (17), (18), and (19), by the Existence and Uniqueness Theorem, there is a unique $ES_{W_1-W_2}^* \in \mathcal{V}$ such that under the sup norm, for all $s \in S$,

$$ES_{W_1-W_2}^*(s_{W_1-W_2}) = \lim_{m \rightarrow \infty} v^m(s_{W_1-W_2}). \quad \parallel \tag{A10}$$

The following Lemmata prove Theorem 2:

Lemma 2. *There exist $\bar{s}^* \geq 0$ and $\underline{s}^* \leq 0$ for some $\bar{s}^*, \underline{s}^* \in S$ such that $\phi^{\bar{s}^*, \underline{s}^*}$ is a dynamically efficient multi-way matching mechanism.*

Proof of Lemma 1. Fix $W_1-W_2 \in \mathcal{P}^{R^*}$. Let $F = \{\text{do-not-match}, \text{match}\}$ and $f_1 = \text{do-not-match}$, $f_2 = \text{match}$. Let

$$h^* \equiv ES_{W_1-W_2}^*$$

and

$$z \equiv s_{W_1-W_2}$$

for notational convenience. The state component space regarding W_1-W_2 and W_2-W_1 types is given by \mathbb{Z} . We rewrite the Bellman equations (17), (18), and (19) as follows: For any $z \in \mathbb{Z}$,

$$h^*(z) = \max_{f \in \{f_1, f_2\}} w(z, f), \tag{A11}$$

where

$$w(z, f) = \frac{\lambda}{\lambda + \rho} [r(z, f) + \sum_{\sigma=z-1}^{z+1} p(\sigma | z, f) h^*(\sigma)], \tag{A12}$$

and $r(z, f)$ is defined by equations (A4) and (A5), and $p(\sigma | z, f)$ is defined by equations (A6) and (A7). For all $z \in \mathbb{Z}$,

$$f^z = \arg \max_{f \in \{f_1, f_2\}} w(z, f) \tag{A13}$$

such that

$$\text{if } w(z, f_1) = w(z, f_2), \text{ then } f_2 = \arg \max_{f \in \{f_1, f_2\}} w(z, f). \tag{A14}$$

For all $z \in \mathbb{Z}$, let

$$\Delta h^*(z) = h^*(z) - h^*(z - 1). \tag{A15}$$

We prove Lemma 2 using the following four claims: ||

Claim 1. Suppose that $z > 0$ is such that $f^z = f_2$, and $f^{z+1} = f_1$. Then there is no $k \geq 1$ such that $f^{z+k+1} = f_2$.

Proof of Claim 1. Let $z > 0$ be such that $f^z = f_2$, and $f^{z+1} = f_1$. We prove the claim by contradiction. Suppose there exists some $k \geq 1$ such that

$$f^{z+2} = f_1, \dots, f^{z+k} = f_1, f^{z+k+1} = f_2.$$

Therefore, by Observation 2 and definitions in equations (A13), (A14), and (A15),

$$\Delta h^*(z) \leq 1, \Delta h^*(z + 1) > 1, \dots, \Delta h^*(z + k) > 1, \text{ and } \Delta h^*(z + k + 1) \leq 1. \tag{A16}$$

By definitions in equations (A11), (A12), (A13), and (A15); for $r(z, f)$ in equations (A4) and (A5); and for $p(\sigma | z, f)$ in equations (A6) and (A7), we obtain

$$\begin{aligned} \Delta h^*(z + 1) &= h^*(z + 1) - h^*(z) = w(z + 1, f_1) - w(z, f_2) \\ &= \frac{\lambda}{\lambda + \rho} \left[\begin{aligned} &\sum_{X-Y \in \mathcal{P}^O(W_1 - W_2)} p_{X-Y} (\Delta h^*(z) - 1) + p_{W_2 - W_1} \Delta h^*(z) \\ &+ (1 - p_{W_1 - W_2} - p_{W_2 - W_1}) \Delta h^*(z + 1) + p_{W_1 - W_2} \Delta h^*(z + 2) \end{aligned} \right] \\ &\leq \frac{\lambda}{\lambda + \rho} [p_{W_2 - W_1} + (1 - p_{W_1 - W_2} - p_{W_2 - W_1}) \Delta h^*(z + 1) + p_{W_1 - W_2} \Delta h^*(z + 2)] \\ &\quad \text{since, by } f^z = f_2, \text{ we have } \Delta h^*(z) \leq 1 \text{ (in Inequality System (A16))} \\ &< [p_{W_2 - W_1} + (1 - p_{W_1 - W_2} - p_{W_2 - W_1}) \Delta h^*(z + 1) + p_{W_1 - W_2} \Delta h^*(z + 2)]. \tag{A17} \\ &\quad \text{since } \frac{\lambda}{\lambda + \rho} < 1 \end{aligned}$$

We rearrange terms in Inequality (A17) to obtain

$$\Delta h^*(z + 1) < \frac{p_{W_2 - W_1}}{p_{W_1 - W_2} + p_{W_2 - W_1}} + \frac{p_{W_1 - W_2} \Delta h^*(z + 2)}{p_{W_1 - W_2} + p_{W_2 - W_1}}. \tag{A18}$$

For all ℓ such that $k \geq \ell > 1$, by definitions in equations (A11), (A12), (A13), and (A15); for $r(z, f)$ in equations (A4) and (A5); and for $p(\sigma | z, f)$ in equations (A6) and (A7), we obtain

$$\begin{aligned} \Delta h^*(z + \ell) &= h^*(z + \ell) - h^*(z + \ell - 1) = w(z + \ell, f_1) - w(z + \ell + 1, f_1) \tag{A19} \\ &= \frac{\lambda}{\lambda + \rho} [p_{W_2 - W_1} \Delta h^*(z + \ell - 1) + (1 - p_{W_1 - W_2} - p_{W_2 - W_1}) \Delta h^*(z + \ell) + p_{W_1 - W_2} \Delta h^*(z + \ell + 1)] \end{aligned}$$

$$\begin{aligned} &< p_{W_2 - W_1} \Delta h^*(z + \ell - 1) + (1 - p_{W_1 - W_2} - p_{W_2 - W_1}) \Delta h^*(z + \ell) + p_{W_1 - W_2} \Delta h^*(z + \ell + 1) \tag{A20} \\ &\quad \text{since } \frac{\lambda}{\lambda + \rho} < 1. \end{aligned}$$

We rearrange terms in Inequality (A20) to obtain

$$\Delta h^*(z + \ell) < \frac{p_{w_2-w_1} \Delta h^*(z + \ell - 1)}{p_{w_1-w_2} + p_{w_2-w_1}} + \frac{p_{w_1-w_2} \Delta h^*(z + \ell + 1)}{p_{w_1-w_2} + p_{w_2-w_1}}. \tag{A21}$$

Using Inequality (A21) for $\ell = k$, and the fact that $\Delta h^*(z + k + 1) \leq 1$ (in equation (A16)), we have

$$\begin{aligned} & (p_{w_1-w_2} + p_{w_2-w_1}) \Delta h^*(z + k) \\ & < p_{w_2-w_1} \Delta h^*(z + k - 1) + (1 - p_{w_1-w_2} - p_{w_2-w_1}) \Delta h^*(z + k) + p_{w_1-w_2} \Delta h^*(z + k + 1) \\ & \leq p_{w_2-w_1} \Delta h^*(z + k - 1) + (1 - p_{w_1-w_2} - p_{w_2-w_1}) \Delta h^*(z + k) + p_{w_1-w_2}. \end{aligned} \tag{A22}$$

We rearrange terms in Inequality (A22) to obtain

$$\Delta h^*(z + k) < \frac{p_{w_2-w_1} \Delta h^*(z + k - 1)}{p_{w_1-w_2} + p_{w_2-w_1}} + \frac{p_{w_1-w_2}}{p_{w_1-w_2} + p_{w_2-w_1}}. \tag{A23}$$

We claim that for any $\ell \in \{1, 2, \dots, k - 1\}$, we have

$$\Delta h^*(z + \ell) < \frac{p_{w_1-w_2} g(\ell - 1) \Delta h^*(z + \ell + 1)}{g(\ell)} + \frac{p_{w_2-w_1}^\ell}{g(\ell)}, \tag{A24}$$

where

$$g(\ell) = \sum_{i=0}^{\ell} p_{w_1-w_2}^i p_{w_2-w_1}^{\ell-i}. \tag{A25}$$

We will prove that Inequality (A24) holds using Inequalities (A18) and (A21) by induction.

- Let $\ell = 1$. Observe that $g(0) = 1$ and $g(1) = p_{w_1-w_2} + p_{w_2-w_1}$ using the definition of g (in equation (A25)). Therefore, by Inequality (A18),

$$\Delta h^*(z + 1) < \frac{p_{w_1-w_2} g(0) \Delta h^*(z + 2)}{g(1)} + \frac{p_{w_2-w_1}}{g(1)}. \tag{A26}$$

- Let $\ell \in \{2, \dots, k - 1\}$. In the inductive step, assume that $\Delta h^*(z + \ell - 1) < \frac{p_{w_1-w_2} g(\ell-2) \Delta h^*(z+\ell)}{g(\ell-1)} + \frac{p_{w_2-w_1}^{\ell-1}}{g(\ell-1)}$. We substitute the right-hand side of this inequality for $\Delta h^*(z + \ell - 1)$ in Inequality (A21) to obtain

$$\begin{aligned} & \Delta h^*(z + \ell) \\ & < \frac{p_{w_2-w_1}}{p_{w_1-w_2} + p_{w_2-w_1}} \left(\frac{p_{w_1-w_2} g(\ell - 2) \Delta h^*(z + \ell)}{g(\ell - 1)} + \frac{p_{w_2-w_1}^{\ell-1}}{g(\ell - 1)} \right) + \frac{p_{w_1-w_2} \Delta h^*(z + \ell + 1)}{p_{w_1-w_2} + p_{w_2-w_1}}. \end{aligned} \tag{A27}$$

We rearrange terms in Inequality (A27) to obtain

$$\Delta h^*(z + \ell) < \frac{p_{w_1-w_2} g(\ell - 1) \Delta h^*(z + \ell + 1) + p_{w_2-w_1}^\ell}{[(p_{w_1-w_2} + p_{w_2-w_1}) g(\ell - 1) - p_{w_2-w_1} p_{w_1-w_2} g(\ell - 2)]}. \tag{A28}$$

Using the definition of g in equation (A25), we observe that

$$(p_{w_1-w_2} + p_{w_2-w_1}) g(\ell - 1) - p_{w_2-w_1} p_{w_1-w_2} g(\ell - 2) = g(\ell). \tag{A29}$$

Substituting $g(\ell)$ for the left-hand side of equation (A29) in Inequality (A28), we obtain

$$\Delta h^*(z + \ell) < \frac{p_{w_1-w_2} g(\ell - 1) \Delta h^*(z + \ell + 1)}{g(\ell)} + \frac{p_{w_2-w_1}^\ell}{g(\ell)}, \tag{A30}$$

completing the induction.

We have $\Delta h^*(z+k-1) < \frac{p_{W_1-W_2} g^{(k-2)} \Delta h^*(z+k)}{g^{(k-1)}} + \frac{p_{W_2-W_1}^{k-1}}{g^{(k-1)}}$ by Inequality (A24). We substitute the right-hand side of this inequality for $\Delta h^*(z+k-1)$ in Inequality (A23) to obtain the following inequality:

$$\Delta h^*(z+k) < \frac{p_{W_2-W_1}}{p_{W_1-W_2} + p_{W_2-W_1}} \left(\frac{p_{W_1-W_2} g^{(k-2)} \Delta h^*(z+k)}{g^{(k-1)}} + \frac{p_{W_2-W_1}^{k-1}}{g^{(k-1)}} \right) + \frac{p_{W_1-W_2}}{p_{W_1-W_2} + p_{W_2-W_1}}. \tag{A31}$$

Rearranging terms in Inequality (A31), we obtain

$$\Delta h^*(z+k) < \frac{p_{W_2-W_1}^k + p_{W_1-W_2} g^{(k-1)}}{(p_{W_1-W_2} + p_{W_2-W_1}) g^{(k-1)} - p_{W_2-W_1} p_{W_1-W_2} g^{(k-2)}}. \tag{A32}$$

Using the definition of g (in equation (A25)), we observe that

$$p_{W_2-W_1}^k + p_{W_1-W_2} g^{(k-1)} = g^{(k)} \text{ and} \tag{A33}$$

$$(p_{W_1-W_2} + p_{W_2-W_1}) g^{(k-1)} - p_{W_2-W_1} p_{W_1-W_2} g^{(k-2)} = g^{(k)}. \tag{A34}$$

Substituting $g^{(k)}$ for the left-hand side terms of equations (A33) and (A34), Inequality (A32) can be rewritten as

$$\Delta h^*(z+k) < 1. \tag{A35}$$

However, Inequality (A35) through Observation 2 contradicts the claim that $f^{z+k} = f_1$ and $\Delta h^*(z+k) > 1$ (stated in Inequality System (A16)). We showed that for any $z > 0$ whenever $f^z = f_2$ and $f^{z+1} = f_1$, there is no $k \geq 1$ such that $f^{z+k+1} = f_2$, completing the proof of Claim 1. \parallel

Claim 2. *There exists $z' \geq 0$ such that for all $z > z'$ we have $f^z = f_2$.*

Proof of Claim 2. Consider a scenario in which there are infinitely many W_1-W_2 type pairs available at the exchange pool. That is, the state component is $z = \infty$. Every incoming overdemanded pair of one of the types in $\mathcal{P}^O(W_1-W_2)$ can be used in an exchange that matches a W_1-W_2 type pair. After such an exchange, there will still be infinitely many W_1-W_2 type pairs, implying that incoming W_2-W_1 type pairs are not affected by the previous decision of choosing largest possible exchanges. Therefore, at state component $z = \infty$, the efficient action is f_2 (option match, conducting largest possible exchanges). Therefore, every incoming W_2-W_1 type pair will be matched in a two-way exchange with a W_1-W_2 type pair, and every incoming pair of one of the types in $\mathcal{P}^O(W_1-W_2)$ will be matched efficiently serving a W_1-W_2 type pair. Since we are discussing the next incoming pairs, this surplus should be discounted with $E[e^{-\rho \tau_1}] = \frac{\lambda}{\lambda + \rho}$. The exchange surplus for the first matched W_1-W_2 or W_2-W_1 type pair in this scenario is

$$\bar{h}^1 = \frac{\lambda}{\lambda + \rho} \left[\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} \left(\frac{c}{\rho} \right) + p_{W_2-W_1} \left(2 \frac{c}{\rho} \right) \right]. \tag{A36}$$

Similarly, the current value of the exchange surplus for the second matched W_1-W_2 or W_2-W_1 type pair is $\bar{h}^2 = \frac{\lambda}{\lambda + \rho} \bar{h}^1, \dots$, and the current value of the exchange surplus for the k^{th} matched W_1-W_2 or W_2-W_1 type pair is $\bar{h}^k = \left(\frac{\lambda}{\lambda + \rho} \right)^{k-1} \bar{h}^1$. Therefore, the total exchange surplus of state component ∞ is

$$\begin{aligned} h(\infty) &= \sum_{k=1}^{\infty} \bar{h}^k = \sum_{k=1}^{\infty} \left(\frac{\lambda}{\lambda + \rho} \right)^{k-1} \bar{h}^1 = \frac{1}{1 - \left(\frac{\lambda}{\lambda + \rho} \right)} \bar{h}^1 \\ &= \frac{\lambda c}{\rho^2} \left(\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} + 2 p_{W_2-W_1} \right). \end{aligned} \tag{A37}$$

By normalizing $h(\infty)$ by $\frac{c}{\rho}$, we obtain

$$h^*(\infty) = \frac{\lambda}{\rho} \left(\sum_{X-Y \in \mathcal{P}^O(W_1-W_2)} p_{X-Y} + 2 p_{W_2-W_1} \right). \tag{A38}$$

Clearly, the normalized exchange surplus at state component ∞ is an upper-bound for the normalized efficient exchange surplus for $z \rightarrow \infty$. Suppose that there is no $z' > 0$ such that for all $z > z'$, $f^z = f_2$. By Claim 1, there exists some $z' > 0$ such that for all $z > z'$, $f^z = f_1$ and $h^*(z) \geq h^*(z-1) + 1$ (by Observation 2). Therefore, for any $z > z'$,

$$h^*(z) \geq (z - z') + h^*(z'). \tag{A39}$$

Then as $z \rightarrow \infty$, $h^*(z) \rightarrow \infty$, contradicting the fact that $h^*(\infty)$ is bounded. This and Claim 1 imply that there exists some $z' > 0$ such that for all $z > z'$, $f^z = f_2$. \parallel

We state the following two claims, whose proofs are symmetric versions of the proofs of Claims 1 and 2:

Claim 3. *Suppose that $z < 0$ is such that $f^z = f_2$, and $f^{z-1} = f_1$. Then there is no $k \geq 1$ such that $f^{z-k-1} = f_2$.*

Claim 4. *There exists $z'' \leq 0$ such that for all $z < z''$ we have $f^z = f_2$.*

By Claims 1 and 2, there exists $\bar{s}_{W_1-W_2}^* \geq 0$ such that $f^z = f_2$ for all $z > \bar{s}_{W_1-W_2}^*$ and $f^z = f_1$ for all $0 \leq z < \bar{s}_{W_1-W_2}^*$. By Claims 3 and 4 there exists $\underline{s}_{W_1-W_2}^* \leq 0$ such that $f^z = f_2$ for all $z < \underline{s}_{W_1-W_2}^*$ and $f^z = f_1$ for all $0 \geq z \geq \underline{s}_{W_1-W_2}^*$. Since $W_1-W_2 \in \mathcal{P}^{R*}$ is arbitrary, the threshold mechanism ϕ^{*,\underline{s}^*} is an efficient matching mechanism.

Lemma 3. *For each $W_1-W_2 \in \mathcal{P}^{R*}$,*

$$ES_{W_1-W_2}^*(0) < \frac{\lambda}{\rho} (p_{W_1-W_2} + p_{W_2-W_1}). \tag{A40}$$

Proof of Lemma 3. Fix $W_1-W_2 \in \mathcal{P}^{R*}$. Consider the state component $z = 0$. If W_1-W_2 and W_2-W_1 type pairs could be matched as soon as they arrived at the exchange pool, the decision problem of the health authority would be trivial and it would match the overdemanded type pairs in the largest possible exchanges. That is, since no W_1-W_2 or W_2-W_1 type pairs remain in the pool unmatched, whenever an $X-Y \in \mathcal{P}^O(W_1-W_2) \cup \mathcal{P}^O(W_2-W_1)$ type overdemanded pair arrives at the exchange pool, it will be matched in an exchange without a W_1-W_2 or W_2-W_1 type pair that matches the maximum number of underdemanded pairs possible and possibly some other reciprocally demanded pairs. Let the associated exchange surplus with this process be $\overline{ES}_{W_1-W_2}(0)$. Since in reality W_1-W_2 and W_2-W_1 type pairs are not matched as soon as they arrive, $\overline{ES}_{W_1-W_2}(0) > ES_{W_1-W_2}(0)$. The exchange surplus related to a pair is $\frac{c}{\rho}$. Since we are discussing the next incoming pair, this surplus should be discounted with $E[e^{-\rho\tau_1}] = \frac{\lambda}{\lambda+\rho}$, implying that the associated exchange surplus is

$$\overline{ES}_{W_1-W_2}^1 = \frac{\lambda}{\lambda + \rho} \left[(p_{W_1-W_2} + p_{W_2-W_1}) \frac{c}{\rho} \right]. \tag{A41}$$

Similarly, the exchange surplus associated with the second incoming pair is $\overline{ES}_{W_1-W_2}^2 = \frac{\lambda}{\lambda+\rho} \overline{ES}_{W_1-W_2}^1, \dots$, and the exchange surplus associated with the k^{th} incoming pair is $\overline{ES}_{W_1-W_2}^k = (\frac{\lambda}{\lambda+\rho})^{k-1} \overline{ES}_{W_1-W_2}^1$. Therefore,

$$\begin{aligned} \overline{ES}_{W_1-W_2}(0) &= \sum_{k=1}^{\infty} \overline{ES}_{W_1-W_2}^k = \sum_{k=1}^{\infty} \left(\frac{\lambda}{\lambda + \rho} \right)^{k-1} \overline{ES}_{W_1-W_2}^1 = \frac{1}{1 - (\frac{\lambda}{\lambda+\rho})} \overline{ES}_{W_1-W_2}^1 \\ &= \frac{\lambda c}{\rho^2} (p_{W_1-W_2} + p_{W_2-W_1}). \end{aligned} \tag{A42}$$

Recall that $ES_{W_1-W_2}^*(0) = \frac{\rho}{c} ES_{W_1-W_2}(0)$. Hence,

$$ES_{W_1-W_2}^*(0) = \frac{\rho}{c} ES_{W_1-W_2}(0) < \frac{\rho}{c} \overline{ES}_{W_1-W_2}(0) = \frac{\lambda}{\rho} (p_{W_1-W_2} + p_{W_2-W_1}). \parallel \tag{A43}$$

Lemma 4. *For each $W_1-W_2 \in \mathcal{P}^{R*}$, we have $\bar{s}_{W_1-W_2}^* \geq 0$ and $\underline{s}_{W_1-W_2}^* = 0$, or $\bar{s}_{W_1-W_2}^* = 0$ and $\underline{s}_{W_1-W_2}^* \leq 0$.*

Proof of Lemma 4. Fix $W_1 - W_2 \in \mathcal{P}^{\mathcal{R}^*}$. We prove the lemma by contradiction. Suppose that there exist some $\bar{s}_{W_1 - W_2}^* > 0$ and $\underline{s}_{W_1 - W_2}^* < 0$ such that $\phi^{\bar{s}^*, \underline{s}^*}$ is efficient. Since $\bar{s}_{W_1 - W_2}^* > 0$, action f_1 (*do-not-match* $W_1 - W_2$ type pair and choose the smaller exchange option) is chosen at state component 1, whenever an action needs to be taken. By the Bellman equation (17), the *normalized* exchange surplus related to action f_1 is $ES_{W_1 - W_2}^*(1)$, the *normalized* exchange surplus related to action f_2 (*match* $W_1 - W_2$ type pair and choose the larger exchange option) is $ES_{W_1 - W_2}^*(0) + 1$, and we have $ES_{W_1 - W_2}^*(1) \geq ES_{W_1 - W_2}^*(0) + 1$ (by Observation 2 and since in case of equality f_2 is chosen). Similarly, since $\underline{s}_{W_1 - W_2}^* < 0$, action f_1 , that is, the smaller exchange, is chosen at state component -1 , whenever an action needs to be taken. By the Bellman equation (18), the *normalized* exchange surplus related to action f_1 is $ES_{W_1 - W_2}^*(-1)$, the *normalized* exchange surplus related to action f_2 (the larger exchange) is $ES_{W_1 - W_2}^*(0) + 1$, and we have $ES_{W_1 - W_2}^*(-1) \geq ES_{W_1 - W_2}^*(0) + 1$ (by Observation 3). We recall the Bellman equation for state component 0 as follows (equation (19)):

$$ES_{W_1 - W_2}^*(0) = \frac{\lambda}{\lambda + \rho} \left[\left(\sum_{X-Y \in \mathcal{P}^{\mathcal{O}}(W_1 - W_2) \cup \mathcal{P}^{\mathcal{U}} \cup \mathcal{P}^{\mathcal{R}} \setminus \{W_1 - W_2, W_2 - W_1\}} p_{X-Y} \right) ES_{W_1 - W_2}^*(0) + p_{W_1 - W_2} ES_{W_1 - W_2}^*(1) + p_{W_2 - W_1} (ES_{W_1 - W_2}^*(-1)) \right]. \tag{A44}$$

We replace $ES^*(1)$ by the smaller number $ES^*(0) + 1$ and $ES^*(-1)$ by the smaller number $ES^*(0) + 1$ in the above expression to obtain the following inequality:

$$ES_{W_1 - W_2}^*(0) \geq \frac{\lambda}{\lambda + \rho} \left[\left(\sum_{X-Y \in \mathcal{P}^{\mathcal{O}}(W_1 - W_2) \cup \mathcal{P}^{\mathcal{U}} \cup \mathcal{P}^{\mathcal{R}} \setminus \{W_1 - W_2, W_2 - W_1\}} p_{X-Y} \right) ES_{W_1 - W_2}^*(0) + p_{W_1 - W_2} (ES^*(0) + 1) + p_{W_2 - W_1} (ES^*(0) + 1) \right]. \tag{A45}$$

Arranging the terms in the above inequality, we obtain

$$ES_{W_1 - W_2}^*(0) \geq \frac{\lambda}{\rho} (p_{W_1 - W_2} + p_{W_2 - W_1}), \tag{A46}$$

contradicting Lemma 3. Therefore, we have $\bar{s}_{W_1 - W_2}^* \geq 0$ and $\underline{s}_{W_1 - W_2}^* = 0$, or $\bar{s}_{W_1 - W_2}^* = 0$ and $\underline{s}_{W_1 - W_2}^* \leq 0$. \parallel

Proof of Theorem 2. The proof follows directly from Lemmata 2, 3, and 4. \parallel

APPENDIX B. ON THE EFFICIENT KIDNEY EXCHANGE MECHANISM WHEN SELF-DEMANDED TYPES PARTICIPATE IN EXCHANGE

In this appendix, we retain Assumptions 1, 2, and 4, and relax Assumption 3, that is, we assume that self-demanded type pairs also participate in exchange. When there are self-demanded types in the exchange pool, under Assumptions 1, 2, and 4, the full state of the matching mechanism should be denoted not only by the difference between the number of A–B and B–A type pairs but also by four other variables that denote the number of O–O, A–A, B–B, and AB–AB type pairs. Next, we outline the intuition behind the derivation of the structure of the efficient mechanism under Assumptions 1, 2, and 4. A formal derivation using Bellman equations is complicated because of the high dimensionality of the state space. However, we can make use of the underlying structure of the problem and our results in the previous subsection in explaining the intuition:

Let $\phi^{\bar{s}^*, \underline{s}^*}$ be the efficient matching mechanism under Assumptions 1, 2, and 4. Without loss of generality, let $\bar{s}^* \geq 0$ and $\underline{s}^* = 0$. Suppose Assumptions 1, 2, and 4 still apply, while self-demanded types can participate in exchange. Two cases can arise in the pool:

- When a self-demanded type pair arrives: Suppose this pair is of type X–X. If there is another type X–X pair available in the exchange pool, then we obtain a two-way exchange by matching these two pairs together

immediately. Observe that this exchange is efficient, since self-demanded pairs cannot save any underdemanded pairs by Proposition 2. Therefore, under the efficient mechanism, there will be 0 or 1 self-demanded type pairs in the pool.

- When a non-self-demanded type pair arrives: Let $E = (i_1, \dots, i_k)$ be a feasible exchange without any self-demanded types (let $i_{k+1} \equiv i_1$). If there exists a self-demanded X–X type pair i available in the exchange pool such that there are pairs i_ℓ and $i_{\ell+1}$ with X blood-type donor and X blood-type recipient, respectively, then we can insert pair i between pairs i_ℓ and $i_{\ell+1}$ and obtain a feasible exchange E' . This exchange is better than E , since (1) self-demanded types cannot save any underdemanded types, (2) overdemanded types are most efficiently used in saving underdemanded types, and finally, (3) self-demanded types can otherwise be matched with only same-type pairs if they are not inserted in larger exchanges. So, we need to enlarge the exchanges as much as possible by inserting all possible existing self-demanded type pairs.

By the above argument, and given the fact that efficient mechanism under Assumptions 1, 2, 3, and 4 is a threshold mechanism, the efficient mechanism under Assumptions 1, 2, and 3 is a *generalized threshold mechanism*, with a threshold number of A–B (or B–A type pairs) to conduct smaller exchanges (the largest exchanges without the A–B or B–A type pairs), where the threshold number depends on the existence or absence of self-demanded type pairs at each state.

Let E_S be the possible smaller exchange and E_L be the possible larger exchange without any self-demanded type pairs. We have the following possibilities for the pair types in E_S and E_L :

| State s | Pair types in E_S | Pair types in E_L |
|---------------------------------|--------------------------------------|------------------------|
| $s < 0$ | (A–O, O–A) | (A–O, O–B, B–A) |
| When $ s $ B–A type pairs exist | (AB–B, B–AB) | (AB–B, B–A, A–AB) |
| | (AB–O, O–A, A–AB), (AB–O, O–B, B–AB) | (AB–O, O–B, B–A, A–AB) |
| $s > 0$ | (B–O, O–B) | (B–O, O–A, A–B) |
| When s A–B type pairs exist | (AB–A, A–AB) | (AB–A, A–B, B–AB) |
| | (AB–O, O–A, A–AB), (AB–O, O–B, B–AB) | (AB–O, O–A, A–B, B–AB) |

Three cases are possible:

- X–X \in {O–O, AB–AB}: Observe that type X–X pair can be inserted in E_S if and only if it can be inserted in E_L in each case. Therefore, the existence of 1 X–X type pair or the absence of X–X type pairs has no effect on the thresholds, since in either case the marginal gain of the larger exchange is only one pair. Therefore, whenever such an X–X type pair exists, inserting the X–X type pair in E_S or E_L , whichever is chosen under the thresholds \bar{s}^* and \underline{s}^* , is the efficient action.
- X–X = A–A: Consider the case when there is 1 A–A type pair. If $\underline{s}^* < 0$ let the pair types of E_S be (AB–B, B–AB) and the pair types of E_L be (AB–B, B–A, A–AB), and if $\bar{s}^* > 0$, let the pair types of E_S be (B–O, O–B) and the pair types of E_L be (B–O, O–A, A–B). In each case, the A–A pair cannot be inserted in the smaller exchange, but it can be inserted in the larger exchange. Therefore, the marginal gain of the larger exchange is two pairs (with A–A type pair). Recall that when no A–A pair exists, the marginal gain of the larger exchange is only one pair. Therefore, the threshold for smaller exchanges with an A–A type pair cannot exceed the threshold without an A–A type pair in absolute value, $|\underline{s}^*|$ or \bar{s}^* , whichever applies. For all other possibilities for E_S and E_L pair types, the A–A type pair can be inserted in E_S if and only if it can be inserted in E_L ; hence the threshold $|\underline{s}^*|$ or \bar{s}^* is still valid for smaller exchanges.
- X–X = B–B: The symmetric argument for the case X–X = A–A applies by interchanging the roles of A and B blood types.

Based on this intuition, we state the following remark:

Remark 1. Suppose Assumptions 1, 2, and 4 hold, i.e. self-demanded type pairs can also participate in exchange. Let $\phi^{\bar{s}^*, \underline{s}^*}$ be the dynamically efficient kidney exchange mechanism under Assumptions 1, 2, 3, and 4. Consider the case $\bar{s}^* > 0$ and $\underline{s}^* = 0$. Then, there exist thresholds $0 \leq \bar{s}_{A-A}^* \leq \bar{s}^*$ and $0 \leq \bar{s}_{B-B}^* \leq \bar{s}^*$ such that under an efficient mechanism whenever a decision is required between two exchanges—the largest exchange with an A–B type pair (option *match*) or the largest exchange without an A–B type pair (option *do-not-match*)—the smaller exchange is chosen if and only if the number of A–B type pairs, s , satisfies

- $\bar{s}_{A-A}^* \geq s \geq 0$, if an A–A type pair exists and a B–O type pair arrives,

- $\bar{s}_{B-B}^* \geq s \geq 0$, if a B–B type pair exists and an AB–A type pair arrives,
- $\bar{s}^* \geq s \geq 0$, otherwise.

If these conditions are not satisfied, the largest exchanges are conducted as soon as they become feasible. The efficient mechanism is symmetrically defined for the case $\bar{s}^* = 0$ and $\underline{s}^* < 0$ with thresholds \underline{s}^* , $0 \geq \underline{s}_{A-A}^* \geq \underline{s}^*$, and $0 \geq \underline{s}_{B-B}^* \geq \underline{s}^*$.³²

We can state a single state variable approximation of the efficient mechanism as follows under Assumptions 1, 2, and 4 with $\underline{s}_{A-A}^* = \underline{s}_{B-B}^* = \underline{s}^*$ and $\bar{s}_{A-A}^* = \bar{s}_{B-B}^* = \bar{s}^*$:

- When a self-demanded type pair arrives: Suppose this pair is of type X–X. If there is another type X–X pair available in the exchange pool, then we obtain a two-way exchange by matching these two pairs together immediately.
- When a non-self-demanded type pair arrives: Let $E = (i_1, \dots, i_k)$ be the efficient exchange according to the efficient mechanism $\phi^{\bar{s}^*, \underline{s}^*}$ without taking the existence of self-demanded types into consideration (let $i_{k+1} \equiv i_1$). If there exists a self-demanded X–X type pair i available in the exchange pool such that there are pairs i_ℓ and $i_{\ell+1}$ with an X blood-type donor and an X blood-type recipient, respectively, then we can insert pair i between pairs i_ℓ and $i_{\ell+1}$ and obtain a feasible exchange E' . We repeat the process with E' until no feasible self-demanded type pair remains to be inserted. We conduct the final exchange obtained.

Let this mechanism be called $\hat{\phi}^{\bar{s}^*, \underline{s}^*}$. We conduct policy simulations using this mechanism.

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32. There could be only one ambiguity in the definition. Suppose that an AB–O type pair becomes available for exchange and a smaller exchange is chosen. Moreover, suppose the number of A–B type pairs is s (such that $0 < s < s^*$). In this case, smaller exchanges are chosen, but we can form two types of exchanges with the AB–O pair.

- We can have a three-way exchange with AB–O, O–A, and A–AB type pairs, or
- We can have a three-way exchange with AB–O, O–B, and B–AB type pairs.

As explained before, by Assumption 1, choosing either exchange is fine when there are no self-demanded types. Consider the case in which there is one A–A and one B–B type pair in the exchange pool. Depending on which exchange is chosen either an A–A or a B–B type pair can be inserted in the exchange, but not both (cf. Proposition 2). When there are self-demanded types, the optimal rule always chooses either the first type of exchange or the second type of exchange depending on the arrival probabilities.

Since in reality incompatible AB–O type pairs are rare, the impact of the tie-breaker is minimal. Moreover, we can make the following approximations: $\bar{s}_{A-A}^* = \bar{s}_{B-B}^* = \bar{s}^*$ and $\underline{s}_{A-A}^* = \underline{s}_{B-B}^* = \underline{s}^*$.

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