Stable Matching with Proportionality Constraints

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Abstract

The problem of finding stable matches that meet distributional concerns is usually formulated by imposing various side constraints. Prior work has focused on constraints whose "right hand sides" are absolute numbers specified before the preferences or number of agents on the "proposing" side are known. In many cases it is more natural to express the relevant constraints as proportions. We treat such constraints as soft, but provide ex-post guarantees on how well the constraints are satisfied while preserving stability. Our technique requires an extension of Scarf's lemma, which is of independent interest.

Keywords: stable matching, diversity, Scarf's lemma

JEL classification: C78, D47

1 Introduction

The elegance and simplicity of Gale and Shapley's deferred acceptance algorithm (DA), Gale and Shapley (1962), has made it the algorithm of choice for determining stable matchings in a variety of settings: doctors to hospitals, students to school seats. Each setting has imposed new demands on the algorithm beyond returning a stable matching that satisfies

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capacity constraints. There is a desire to satisfy side constraints motivated by equity and distributional considerations.

It is usual to express the relevant constraints as proportions. As an example, in 1989, the city of White Plains, New York required each school to have the same proportions of Blacks, Hispanics, and “others”, a term that includes Whites and Asians. The plan allowed for a discrepancy among schools of only 5 percent. Similarly, the 2003 Cambridge, Massachusetts Public School District’s goal for a matching was for each grade in each school to be within a range of plus or minus 15 percentage points of the district-wide percentage of low-SES students.[1]

In prior work, these constraints are translated into absolute numbers. For example, a requirement that at least 10 percent of students in a school with capacity 100 belong to a particular SES becomes a constraint that at least 10 students in the school belong to the relevant SES. This assumes that each school will be fully allocated. If the number of students is less than the number of slots, this clearly cannot be be true. The Chicago Public Schools (CPS), the third largest in the US, for example, saw a drop in enrollment from 426,215 in 2000 to about 350,535 in 2013. It classifies almost 50 percent of Chicago’s public schools as half-empty.[2] Even if the number of students exceeds the number of slots, whether a school is fully allocated or not depends on the actual matching and the outside options of the students.

In this paper, we consider both lower and upper bound constraints on the proportions of students from each category. Constraints on proportions have the advantage of not committing to an absolute number as a target. Insofar as we are aware, propotionality constraints have not previously been incorporated into stable matching problems.

The first contribution of this paper is a definition of stability adapted to the case of

[1]See Case Studies of School Choice and Open Enrollment in Four Cities, (Cowen Institute, 2011).

[2]Other school districts facing steep enrollment declines are Buffalo, Philadelphia, Columbus (Ohio), Pittsburgh, Cleveland, Detroit and Kansas City.

proportionality constraints. Adaptation is required because proportionality constraints are implicit capacity constraints. To see why, suppose the number of minority students applying to a given school is 10. Suppose also that the school must ensure that at least 20 percent of admitted students be minority. To satisfy this proportionality constraint, the school cannot admit more than $\frac{10}{20\%} = 50$ students. This could be below the actual capacity of the school. Furthermore, the "effective capacity" implied by the proportionality constraint depends endogenously on the matching. For example, suppose that among the 10 minority students applying to this school, 4 are accepted to schools they prefer more and which will accept them. The given school's effective effective capacity will be reduced to $\frac{6}{20\%} = 30$. The effect on capacity is compounded with the introduction of upper bound proportionality constraints as well.

Satisfying both stability and proportionality constraints in general is impossible. So, we treat the proportionality constraints as soft, but provide ex-post guarantees on how well they are satisfied while preserving stability. Our algorithm relies on the technique introduced in Nguyen and Vohra (2016), which is based on Scarf's lemma. Adapting it to proportionality constraints requires a significant generalization of the lemma, which is of independent interest. This generalization establishes the existence of a "fractional" stable matching that satisfies the proportionality constraints. Subsequently, this fractional matching is rounded into an integral stable matching that only violates the proportionality constraints (but not the capacity constraints) in a limited way.

Below we briefly summarize prior work emphasizing its differences with this paper. Section 2 defines lower bound proportionality constraints and the notion of stability. Section 3 introduces Scarf's lemma and extends it to problems with lower bound proportional constraints. Section 4 describes the algorithm. Section 5 analyzes the stability of the rounded solution. Section 6 extends the result to upper bound proportionality constraints and gives an explicit algorithm. We conclude in Section 7.

1.1 Related Work

There is now a large collection of papers devoted to finding stable matchings under distributional constraints. No attempt is made to provide a comprehensive survey here. However, all prior work can be be placed into one of four categories that we list below and give illustrative examples of papers in each category.

- Ceilings

  Distributional concerns are modeled as ceilings on the number of agents of each type from the 'proposing' side that can be accepted. Ceiling constraints are generally considered easy to accommodate (see Abdulkadiroglŭ and Sönmez (2003)). Regional capacity constraints are ceilings that apply to subsets on the "accepting" side rather than just individual members. As long as the subsets have a laminarity property, satisfying these constraints as well as the stability is not difficult. See Fleiner and Kamiyama (2012) and Kojima et al. (2014) for examples. Ceiling constraints, however, can disadvantage minorities. This is discussed in Hafalir et al. (2013).

- Floors

  Instead of imposing ceilings, one imposes floors on the number of proposers of a particular type. Satisfying floors and stability is generally difficult to do. This is discussed in Biró et al. (2010)) and Huang (2010) which also describe some solvable cases.

- Set Asides

  Instead of ceilings and floors, one sets aside capacity for each subgroup and then run a separate matching process for each subgroup. This approach generally produces inefficiencies and other perverse effects in the resulting matching (see Kojima (2012) and Ellison and Pathak (2016)), which are subsequently addressed by adjusting the set asides either dynamically or ex-post (see Fragiadakis and Troyan (2016) and Aygun and Turhan (2016) for examples).

- Modifying Priorities

  Instead of focusing on floors and ceilings, one modifies the choice function on the "accepting" side so as to favor various groups. If the modified choice function is specified in the right way, the DA algorithm (or some variant) will find a stable matching. However, there is no ex-post guarantee on realized distribution.[3] An example of this approach can be found in Ehlers et al. (2014). In lieu of an ex-post guarantee, some authors focus on priorities that will produce distributions that are closest to a target distribution, see Erdil and Kumano (2012) for an example.

In the first three cases the relevant "right-hand sides" are quantities specified *before* agents on the "proposing" side make their participation decisions. This may over-constrain the problem because the number of "proposers" who will be matched is not known in advance but is rather endogenous. In the remaining cases, targeted groups are 'favored' but no guarantee is provided on the realized distribution.

2 Matching with Proportionality Constraints

To describe the stable matching problem we use the language of doctors and hospitals to distinguish between the two sides of the market. Denote by H the set of hospitals and D the set of doctors. Each doctor $d \in D$ has a strict preference ordering $\succ_d$ over $H \cup \{\varnothing\}$, where $\varnothing$ denotes the outside option for each doctor. If $\varnothing \succ_d h$, we say that hospital h is not acceptable for d. Each hospital $h \in H$ has capacity $k_h > 0$ and a strict priority ordering $\succ_h$ over elements of $D \cup \{\varnothing\}$. If $\varnothing \succ_h d$, we say d is not acceptable for h.

A matching is an assignment of each doctor to a hospital or his/her outside option; each hospital is assigned an acceptable set of doctors that does not exceed its capacity. Given a matching μ, let $\mu(h)$ denote the subset of doctors matched to h and $\mu(d)$ denote the

[3] If one is not careful, there is also a "circularity" problem, in that stability is defined with respect to the modified choice function.

position that d obtains in the matching. Thus μ satisfies:

$$\begin{aligned} i) &\quad \mu(d) \succ_d \varnothing \\ ii) &\quad \text{if } d \in \mu(h) \text{ then } d \succ_h \varnothing \\ iii) &\quad |\mu(h)| \leq k_h \end{aligned} \tag{1}$$

Next, we introduce the proportionality constraints for hospitals. For each hospital h, let $D^h := \{d : d \succ_h \varnothing, h \succ_d \varnothing\}$ be the set of doctors acceptable to h who find h acceptable. Each D^h is partitioned into T_h sets:

$$D^h = D^h_1 \cup D^h_2 \cup .. \cup D^h_{T_h}.$$

Different hospitals can have different partitions. A doctor $d \in D^h_t$ is said to be of type t for hospital h. The type of a doctor may represent a characteristic like intended specialty. In the school choice context, where hospitals correspond to schools and doctors to students, a type can represent an SES category. Allowing different schools to have different partitions allows schools the flexibility to use categories depending on the proximity of the student's residence to the school.[4]

The lower bound proportionality constraint at each hospital $h \in H$ is

$$\alpha^h_t \cdot |\mu(h)| \leq |\mu(h) \cap D^h_t| \ \forall t = 1, \ldots, T_h, \text{ where } 0 \leq \alpha^h_t \leq 1, \sum_t \alpha^h_t \leq 1. \tag{2}$$

A matching satisfying (1) and (2) is called **feasible.**

Constraint (2) ensures that the proportion of doctors of each type in D^h who are matched to hospital h is above some threshold. These constraints don't need to hold for each hospital-

[4]Here we assume the categories are disjoints. Our model can be extended to capture overlapping categories.

type pair. This can be captured by setting $\alpha_t^h = 0$. Unlike floor constraints, the left-hand side of (2) are endogenous.

Our goal is to find a feasible stable matching. Stability in the presence of (2) is defined below. We denote an instance of the problem by $(\{\succ_d\}_{d\in D}, \{\succ_h\}_{h\in H}, \{\alpha^h\}_{h\in H}, \{k_h\}_{h\in H})$. As a feasible stable matching need not exist, we derive a feasible stable matching, $\bar{\mu}$ for a nearby instance $(\{\succ_d\}_{d\in D}, \{\succ_h\}_{h\in H}, \{\bar{\alpha}^h\}_{h\in H}, \{k_h\}_{h\in H})$ where $|\alpha_t^h - \bar{\alpha}_t^h| \le \frac{2}{|\bar{\mu}(h)|}$ for all h and t. The precise form can be found in Section 4.3. The inverse dependence on $\bar{\mu}(h)$ is unavoidable. Small changes in the number of doctors of type t matched to h can have big effects on the proportion of such doctors if $|\bar{\mu}(h)|$ is small.

Our results extend to the case with both upper *and* lower bounds on the proportions of each type to be matched as well. This is described in Section 6. That section also describes an explicit algorithm for determining the matching.

2.1 Stability

A feasible matching is blocked if there is a doctor-hospital pair that would prefer to be matched to each other rather than the partners assigned to them in the matching. In the presence of (2) we must modify the usual notion of blocking to rule out blocking pairs that violate (2).[5] Example 2.1 shows why such a modification is required.

EXAMPLE 2.1. *Consider a single hospital h with capacity 3 and priority order*

$$d_1 \succ_h d_3 \succ_h d_4 \succ_h d_2.$$

Let $D = \{d_1, d_2, d_3, d_4\}$ with $D_1^h = \{d_1, d_2\}$ and $D_2^h = \{d_3, d_4\}$. All doctors strictly prefer to be

[5]This is standard, see Kamada and Kojima (2014) for example.

matched to h than remain unmatched. We impose the following side constraint.

$$\frac{2}{3}|\mu(h)| \leq |\mu(h) \cap D_1^h|. \tag{3}$$

Consider the matching μ that assigns d_1, d_2, d_3 to h. Observe that (3) binds at this matching. In the absence of (3), (d_4, h) would be a blocking pair because h prefers d_4 to d_2. However, h cannot accept d_4 without violating (3). Thus, the proportionality constraints can conflict with the priority order of hospitals.

The idea behind the modification is to consider only blocking pairs that violate neither the capacity nor the proportionality constraints. To this end we define for each feasible matching a set of protected doctors and for each hospital its effective capacity. A protected doctor can never be rejected by any hospital they are matched to in favor of another doctor.

We start with the notion of wait-listed doctors.

Definition 2.1 (Wait-listed Doctor). *Given a feasible matching μ, a doctor d is* **wait-listed** *at h if either d is unmatched and $d \succ_h \varnothing$, or $h \succ_d \mu(d)$.*

Thus, the wait-listed doctors of a hospital h are those who prefer to be matched with h over their current outcome. In other words, each of these doctors would like to form a blocking coalition with h.

Fix a hospital h. Suppose the set of doctors of type t at this hospital, D_t^h, does not contain any wait-listed doctors. Then, h cannot increase the number of admitted doctors of type t because all such doctors are already matched to a more preferred hospital. In this case, the proportionality constraint corresponding to type t, $\alpha_t^h|\mu(h)| \leq |\mu(h) \cap D_t^h|$, implies that the total number of doctors that hospital h can accept is at most

$$\frac{1}{\alpha_t^h}|\mu(h) \cap D_t^h|.$$

This motivates the following definition of a hospital's effective capacity.

Definition 2.2 (Effective Capacity). *Consider a feasible matching μ and a hospital h. Let T_0 be the set of types t, such that D_t^h contains no wait-listed doctor. Denote hospital h's effective capacity with respect to μ by k_h^μ, where*

$$k_h^\mu := \min\{k_h, \min_{t \in T_0} \frac{1}{\alpha_t^h} |\mu(h) \cap D_t^h|\}.$$

If $T_0 = \varnothing$, $k_h^\mu = k_h$.

Remark 1. *Given μ, k_h^μ is an upper bound on the number of positions that h can fill by accepting more wait-listed doctor without violating any proportionality constraints. Because μ is feasible, it satisfies both the capacity and the side constraints. Thus, it is clear that $|\mu(h)| \leq k_h^\mu$.*

From the definition above, if hospital h is not at its effective capacity with respect to μ, $|\mu(h)| < k_h^\mu$, then

- *$|\mu(h)| < k_h$, and*
- *there is no $t \in T_0$ such that the proportionality constraint corresponding to D_t^h binds, that is, $|\mu(h)| = \frac{1}{\alpha_t^h} |\mu(h) \cap D_t^h|$.*

In what follows, when μ is clear from context we will omit the qualifier 'with respect to μ' when referring to a hospitals effective capacity. Next we define the types of doctors who are protected.

Definition 2.3 (Protected Type of Doctors). *Given a feasible matching μ, the set of type t doctors at hospital h, is* **protected** *with respect to μ if (2) binds with respect to the effective capacity, that is*

$$|\mu(h) \cap D_t^h| = \alpha_t^h \cdot k_h^\mu. \tag{4}$$

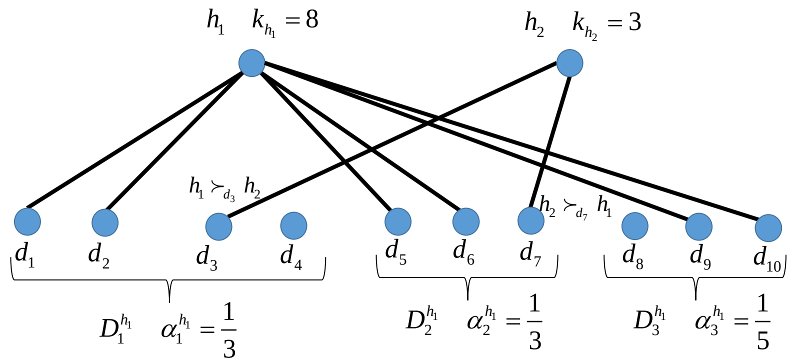

Figure 1: An example of effective capacity and protected doctors

In what follows, when μ is clear from context we will omit the qualifier 'with respect to μ' when referring to protected doctors.

Example 2.2. *We illustrate the definition of effective capacity and protected doctor using Figure 1.*

Consider the group $D_2^{h_1}$. Doctor d_7 is the only member of $D_2^{h_1}$ not matched to h_1 and she prefers h_2 to h_1. Thus, the group $D_2^{h_1}$ does not contain any wait-listed doctor. This means that h_1 cannot admit more doctors from $D_2^{h_1}$. Together with the proportionality constraint for group $D_2^{h_1}$, it implies that hospital h_1 cannot admit more than $2/(\alpha_2^{h_1}) = 6$ doctors. The effective capacity of h_1 becomes 6 instead of its original capacity of 8.

As the effective capacity of h_1 is 6, the proportionality constraints corresponding to $D_1^{h_1}$ and $D_2^{h_1}$ bind, thus $D_1^{h_1}$ and $D_2^{h_1}$ are protected. If a type is protected, it means that the hospital cannot decrease the number of doctors of this type who are matched to it. Why? If the hospital decreases this number, it will also need to decrease the total number of doctors to satisfy the proportionality constraints.

To motivate the definition of stability below, consider d_3, who prefers to be matched with h_1 rather than his current match, h_2. As h_1 is at its effective capacity, h_1 must reject a doctor currently matched to h_1 in order to accept d_3. To satisfy the proportionality constraint, h_1

can only reject either a doctor of the same type as d_3 (d_1 or d_2), or an unprotected doctor (d_9 or d_{10}). The definition below requires this matching to be stable if h_1 has no incentive to replace d_3 with any of these doctors. That is, h_1 prefers each of d_1, d_2, d_9 and d_{10} to d_3.

Next, we introduce the notion of stability motivated by example 2.2.

DEFINITION 2.4 (Bilateral Stability). *A feasible matching μ is (bilaterally)* **stable** *if it satisfies the following two conditions:*

1. *Each hospital is at its effective capacity, that is $|\mu(h)| = k_h^{\mu}$.*

2. *If d_a is on the wait list of h , $d_r \in \mu(h)$ and $d_a \succ_h d_r$, then d_a is protected and d_a and d_r are not of the same type.*

The first condition ensures that no hospital can increase the number of doctors it accepts. The second condition ensures that if h tries to reject d_r to accept a better d_a, then it will violate the side constraint. This is because d_r is protected and d_a is not of the same type as d_r, thus by rejecting d_r hospital h will violate the side constraint of the group containing d_r.

We show that (bilateral) stability implies coalitional stability. To do so we must specify each hospital's preferences over subsets of D. This is summarized by h's choice function $Choice_h(.) : 2^D \to 2^D$.

DEFINITION 2.5. *The choice function of h on a subset of acceptable doctors D^*, denoted $Choice_h(D^*)$, is the subset of D^* with largest cardinality that satisfies the capacity constraints of h and the proportionality constraints. If there are multiple such subsets, then $Choice_h(D^*)$ is the best one in the lexicographical order according to $\succ_h$.*

If $\alpha_t^h = 0$ for all h and t, this choice function reduces to being responsive: for any set $D^* \subset D$, hospital h's choice from D^*, consists of the (up to) k_h highest priority doctors among the feasible doctors in D^*. Responsiveness is a standard assumption in the literature.

With this we have the following theorem.

Theorem 2.1. *Let μ be a stable matching, then for any group of doctors D^* on the wait list of h, $Choice_h(\mu(h) \cup D^*) = \mu(h)$.*

Proof. First notice that because h is at its effective capacity, h cannot increase the number of doctors without violating the proportionality constraints. Thus,

$$|Choice_h(\mu(h) \cup D^*)| = |\mu(h)|.$$

Let $D_A := Choice_h(\mu(h) \cup D^*) \setminus \mu(d)$ be the set of accepted doctors. Let $D_R := \mu(d) \setminus Choice_h(\mu(h) \cup D^*)$ be the set of rejected doctors. Assume D_A and D_R are not empty. Let d_{min} be the lowest ranked doctor among D_R according to $\succ_h$. Because h breaks ties according to the lexicographical order, all doctors in D_A must be more preferred than d_{min}.

If d_{min} is unprotected, then it is a contradiction to the definition of bilateral stability because any $d_a \in D_A$ can replace d_{min} at h. If d_{min} is protected then in order to keep the side constraint of this type, h needs to accept a doctor of the same type. Thus, there should be a $d_a \in D_A$ that is of the same type as d_{min}. In this case we can replace d_{min} with a better doctor, d_a, which is a contradiction to the definition of bilateral stability. Hence D_A and D_R are empty and thus, $Choice_h(\mu(h) \cup D^*) = \mu(h)$. □

3 Fractional Stable Matching

This section is the technical heart of the paper. We use Scarf's lemma to obtain a fractional stable matching. A direct application of the lemma will not accommodate (2). We derive what we call a 'conic representation' of the lemma. This is both new and general enough to apply to other types of side constraints, but in this paper we confine ourselves to proportionality constraints.

We first describe Scarf's lemma and show how it can be applied to matching.

3.1 Scarf's Lemma

Definition 3.1. *Let $\mathcal{A}$ be an $m \times n$ nonnegative matrix with at least one positive entry in each row and column and $b \in \mathbb{R}^m_+$ be a positive vector. Associated with each row i of $\mathcal{A}$ is a strict ranking $\succ_i$ over the columns in $\{1 \leq j \leq n : \mathcal{A}_{ij} > 0\}$. Let $\mathcal{P} = \{x : x \geq 0, \mathcal{A}x \leq b\}$. We say $x \in \mathcal{P}$* **dominates** *column j if there exists a row i such that:*

- *$\mathcal{A}_{ij} > 0$ and the constraint i binds, that is, $(\mathcal{A}x)_i = b_i$ and*
- *$k \succ_i j$ for all columns $k \neq j$ such that $\mathcal{A}_{ik}x_k > 0$.*

In this case we say that x dominates column j via row i.

Theorem 3.1 (Scarf (1967)). *There exists an extreme point of $\mathcal{P}$ that dominates every column of $\mathcal{A}$.*

To understand the connection of domination to stability, it is helpful to consider the matching problem without side constraints. For each $d \in D \cup \{\varnothing\}$ and $h \in H \cup \{\varnothing\}$ let $x(d,h) = 1$ if we assign d to h and zero otherwise. Now, each doctor $d \in D$ can be assigned to at most one hospital:

$$\sum_{h \in H \cup \varnothing} x(d,h) \leq 1 \ \forall d \in D. \tag{5}$$

Each hospital h can be assigned at most k_h doctors:

$$\sum_{d \in D \cup \varnothing} x(d,h) \leq k_h \ \forall h \in H. \tag{6}$$

Each inequality (5) inherits the order that doctor d, i.e., $\succ_d$, has over $H \cup \{\varnothing\}$. Each inequality (6) inherits the priority ordering that hospital h, i.e., $\succ_h$, has over $D \cup \{\varnothing\}$. As follows, system (5-6), along with a non-negativity restriction on the x variables, satisfies the conditions of Scarf's lemma.

Now, as is well known, every non-negative extreme point of (5-6) corresponds to a matching. By Scarf's lemma, one of these extreme points, x^*, say, is dominating. To show that the matching implied by x^* is stable, suppose a pair (d^*, h^*) such that $x^*(d^*, h^*) = 0$. We show that (d^*, h^*) cannot be a blocking pair. By domination, there must exist a binding constraint from (5-6). Either it is indexed by d^* or h^*. Say, d^*. Then,

$$\sum_{h \in H \cup \{\varnothing\}} x^*(d^*, h) = 1.$$

As $x^*(d^*, h^*) = 0$ it follows that exactly one $h' \in H \cup \{\varnothing\}$ exists such that $x^*(d^*, h') = 1$. Further, by domination, $h' \succ_{d^*} h^*$, which means (d^*, h^*) cannot be a blocking pair.

The side constraints in (2) can be written as

$$\alpha_t^h \cdot \sum_{d \in D} x(h,d) \leq \sum_{d \in D_t^h} x(h,d) \ \forall t = 1, \ldots, T_h, \ \forall h \in H. \tag{7}$$

It is tempting to append inequality (7) to (5-6) and invoke Scarf's lemma. However, it is not possible. If we rewrite (7) in the form $\mathcal{A}x \leq b$, the relevant inequalities have negative coefficients and the corresponding coordinates of b are 0. Therefore, Scarf's lemma does not apply. Also, the condition of stability in our setting is now endogenous and depends on the effective capacity of a hospital. It is not clear how one can apply Scarf's lemma directly as in Nguyen and Vohra (2016).

3.2 Conic Representation

We need another approach to determine a dominating solution of (5-6) that satisfies (7). We exploit the fact that the constraints in (7) form a polyhedral cone. Therefore, any point in the cone can be expressed as a non-negative linear combination of its generators. We give a high level description first.

Consider the problem of finding a dominating solution satisfying resource constraints $\mathcal{A}x \leq b$ and side constraints $\mathcal{M}x \geq 0$. The set $\{x \in \mathbb{R}^n_+ | \mathcal{M}x \geq 0\}$ is a polyhedral cone and can be rewritten as $\{\mathcal{V}z | z \geq 0\}$, where $\mathcal{V}$ is a finite non-negative matrix. The columns of $\mathcal{V}$ correspond to the **generators** of the cone $\{x \in \mathbb{R}^n_+ | \mathcal{M}x \geq 0\}$. The 'trick' is to apply Scarf's lemma to $\mathcal{Q} = \{z \geq 0 : \mathcal{A}\mathcal{V}z \leq b\}$. To do so, we need to endow each row of $\mathcal{A}\mathcal{V}$ with an ordering so that domination with respect to this system will correspond to stability.

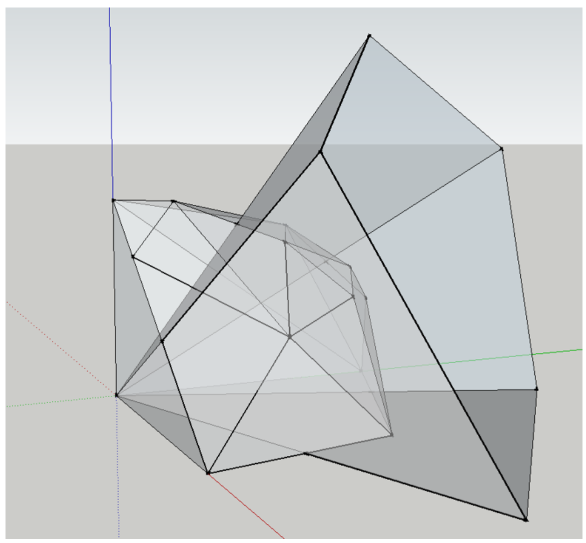

Figure 2: Geometric presentation

Figure 2 gives a geometric illustration of (5, 6, 7). The polytope in Figure 2 corresponds to the matching polytope (5, 6). The inequalities (7) are represented by the cone. The conic version of Scarf's lemma gives us a fractional dominating solution, x^*, say, that is inside the cone but on the boundary of the matching polytope. In particular, there is no other point in the matching polyhedron that vector dominates x^*. Our rounding algorithm, described in the next section, will round x^* into an integral solution on the boundary of the polytope, but possibly outside the cone.

Next, we show how to determine the generators of the cone associated with (7).

Generators of a Cone

The following is standard (see Nemhauser and Wolsey (1988)).

LEMMA 1. *For any matrix $\mathcal{M}$, if the set $\{x \in \mathbb{R}^n_+ | \mathcal{M}x \geq 0\}$ contains a non-zero vector, there exists a finite set of non-negative vectors $\mathcal{V}$ such that this set can be expressed as*

$$\{\sum_{v_i \in \mathcal{V}} z_i v_i | z_i \geq 0\}.$$

The set of vectors, $\mathcal{V}$, are called the **generators** *of $\{x \in \mathbb{R}^n_+ | \mathcal{M}x \geq 0\}$.*

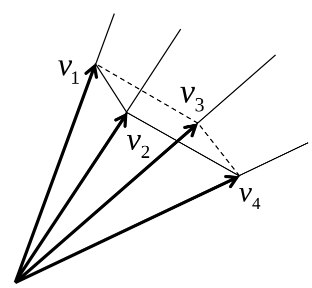

Figure 3: Cone and its generators

The proportionality constraints are of the form $\mathcal{M}x \geq 0$. To determine the generators of (7), fix a hospital $h \in H$ and focus on

$$\alpha^h_t \cdot \sum_{d \in D} x(h,d) \leq \sum_{d \in D^h_t} x(h,d) \;\; t = 1, \ldots, T_h. \tag{8}$$

It is straightforward to see that the generators can be described in this way:

1. Select one doctor from each D^h_t and call it d_t.

2. Select an extreme point of the system

$$\sum_{t=1}^{T_h} v(d_t, h) = 1, \;\; \alpha^h_t \leq v(d_t, h) \;\; \forall t = 1, \ldots, T_h.$$

An extreme point can be determined using the following two-step procedure.

(a) Choose an index $t^* \in \{1, \ldots, T_h\}$ and and set $v(d_{t^*}, h) = 1 - \sum_{t \neq t^*} \alpha_t^h \geq \alpha_{t^*}^h$.

(b) For all $t \neq t^*$, set $v(d_t, h) = \alpha_t^h$.

As there are T_h types of doctors, and each type contains $|D_t^h|$ doctors, the number of generators associated with hospital h can be as large as $T_h \cdot \prod_t |D_t^h|$.[6]

Let $\mathcal{V}_h$ be the set of generators associated with hospital h. Each $v \in \mathcal{V}_h$ has T_h non-zero coordinates and can be interpreted as a probability vector. Thus, from the point of view of each $h \in H$, each $v \in \mathcal{V}_h$ can be seen as a lottery over doctors in D.

We illustrate with an example.

EXAMPLE 3.1. *Suppose $H = \{h_1, h_2\}$ and 2 doctors $d_1 \in D_1^{h_1}$ and $d_2 \in D_2^{h_1}$. Hospital h_2 considers all doctors to be the same type, i.e., $D_1^{h_2} = \{d_1, d_2\}$.*

The only proportionality constraints are imposed on h_1: the number of type 1 doctors should be at least 1/3 of the total number of doctors assigned to h_1. This constraint can be written as

$$\frac{1}{3}[x(d_1, h_1) + x(d_2, h_1)] \leq x(d_1, h_1)$$

The set of generators for this constraint are

$$\mathcal{V}_{h_1} = \{(1/3, 2/3); (1/3, 2/3)\} := \{v_1, v_2\}.$$

We can interpret $v_1 = (1/3, 2/3)$ to mean assigning d_1 and d_2 to h_1 with probability 1/3 and 2/3 respectively. All solutions satisfying the proportionality constraints at h_1 can be expressed as a linear combination of v_1 and v_2.

There are no proportionality constraints imposed on h_2. This is the same as setting

[6] The number of types, T_h, will typically be a small constant. Hence, the number of generators is polynomial in the number of doctors.

$\alpha_1^{h_2} = 0$. *The set of generators for* h_2 *are*

$$\mathcal{V}_{h_2} = \{(1,0),(0,1)\} := \{v_3, v_4\}.$$

We interpret $v_3 = (1,0)$ *to mean assigning* d_1 *to* h_2 *with probability 1, and* d_2 *to* h_2 *with probability zero.*

3.3 Conic version of Scarf's lemma

Associated with each hospital $h \in H$ is a set $\mathcal{V}_h$ of generators. Let $\mathcal{V}$ be the matrix whose columns correspond to the generators in $\bigcup_{h\in H} \mathcal{V}_h$. Let $\mathcal{A}$ be the constraint matrix associated with (5-6). Each row of the matrix $\mathcal{A}\cdot\mathcal{V}$ corresponds to an element of either D or H. The columns of $\mathcal{A}\cdot\mathcal{V}$ correspond to the set of generators. For each $h \in H$, a column in $\mathcal{A}\cdot\mathcal{V}$ that corresponds to $v \in \mathcal{V}_h$, will have a '1' in the h^{th} row and $v(d,h)$ in the d^{th} row. All other entries in that column will be zero. Let $z \in \mathbb{R}_+^{|\bigcup_{h\in H} \mathcal{V}_h|}$ be a non-negative weight vector on the set of generators. The constraints $\mathcal{A}\cdot\mathcal{V}\cdot z \le b$ can be interpreted as follows:

- For each hospital h, the total weight of generators in $\mathcal{V}_h$ is at most k_h.
- For each doctor d, the weight of generators that assigns d to a hospital is at most 1.

EXAMPLE 3.2. *Consider example 3.1. Suppose* $k_h = 2$. *The polyhedron* $\mathcal{Q}$ *is displayed below.*

$$\begin{array}{c} \\ d_1 \\ d_2 \\ h_1 \\ h_2 \end{array}
\begin{array}{c} \begin{array}{cccc} v_1 & v_2 & v_3 & v_4 \end{array} \\ \begin{bmatrix} 1/3 & 2/3 & 1 & 0 \\ 2/3 & 1/3 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \end{array} \cdot z \le \begin{bmatrix} 1 \\ 1 \\ 2 \\ 2 \end{bmatrix}$$

To invoke Scarf's lemma we need each row of $\mathcal{A}\mathcal{V}$ to have a strict ordering over the columns, i.e., generators, in its support. The support of each generator corresponds to one hospital and a coalition of doctors, at most one of each type.

1. For each $h \in H$ we order the generators in $\mathcal{V}_h$ lexicographically. Given $v, v' \in \mathcal{V}_h$, among the doctors who are assigned by v, v' with positive probability to h, let d_1 and d_1' be the lowest ranked doctors (according to $\succ_h$). If $d_1 \succ_h d_1'$, then h ranks v over v'. We will write this as $v \succ_h v'$. If $d_1 = d_1'$, we compare $v(d_1, h)$ and $v'(d_1, h)$. If $v(d_1, h) > v'(d_1', h)$, then h ranks v over v', i.e., $v \succ_h v'$. If it is the reverse, then, $v' \succ_h v$. If $v(d_1, h) = v'(d_1', h)$, move to the next lowest ranked doctor in each generator and so on. Because $v \neq v'$, this procedure must terminate in an unambiguous ordering.

2. For each $d \in D$ and any $v, v' \in \cup_{h \in H} \mathcal{V}_h$, we rank v above v' if v assigns d to a higher ranked hospital (according to $\succ_d$) than v' does. We write this as $v \succ_d v'$. If $v, v' \in \mathcal{V}_h$ for some $h \in H$, then, $v \succ_d v'$ if $v(d, h) > v'(d, h)$ and the reverse otherwise. If $v(d, h) = v'(d, h)$ we order v and v' in the same way that h would.

Example 3.3. *Continuing example (3.1), let $h_1 \succ_d h_2$ for all $d \in D$ and $d_1 \succ_h d_2$ for all $h \in H$. The order of each element of $D \cup H$ over the set of generators is displayed below.*

$$\begin{array}{c} \\ d_1 \\ d_2 \\ h_1 \\ h_2 \end{array} \begin{array}{c} \begin{array}{cccc} v_1 & v_2 & v_3 & v_4 \end{array} \\ \begin{bmatrix} 1/3 & 2/3 & 1 & 0 \\ 2/3 & 1/3 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \end{array} \cdot z \leq \begin{bmatrix} 1 \\ 1 \\ 2 \\ 2 \end{bmatrix}; \; order: \begin{array}{l} v_1 \succ_{d_1} v_2 \succ_{d_1} v_3 \\ v_2 \succ_{d_2} v_1 \succ_{d_2} v_4 \\ v_2 \succ_{h_1} v_1 \\ v_3 \succ_{h_2} v_4 \end{array}$$

Consider the order for h_1 on v_1, v_2. Because they both assign d_1 and d_2 to h_1, we need to compare the probability of assigning d_2, which is the worst doctor for h_1. Because v_1 assigns d_2 with higher probability, $v_2 \succ_{h_1} v_1$.

Consider the order for d_1 on v_1, v_2 and v_3. Because v_1, v_2 assigns d_1 to h_1, and v_3 assigns d_1 to h_2, thus d_1 prefers both v_1 and v_2 to v_3. Between v_1 and v_2, the one that assigns with a lower probability is better, and thus $v_1 \succ_{d_1} v_2$.

REMARK 2. *By Theorem 3.1, there exists a dominating solution of $\mathcal{Q}$, call it z^*. Let*

$$\mathcal{V}^* = \{v \in \mathcal{V} : z_v^* > 0\} \tag{9}$$

be the set of generators with positive z^* weight. Denote by $\mathcal{V}_h^*$ the subset of generators in $\mathcal{V}^*$ that assign doctors to h and similarly denote by $\mathcal{V}_d^*$ the subset of generators in $\mathcal{V}^*$ that assign d to a doctor. Because z^* is a dominating solution, for every generator v that assigns a group of doctors $d_1, ..., d_{T_h}$ to h, one of the following must be true:

- *The constraint $\mathcal{Q}$ corresponding to h binds. That is, h is fully allocated and h ranks all the generators in $\mathcal{V}_h^*$ over v.*
- *There is a $d_i \in \{d_1, ..., d_{T_h}\}$ such that the constraint in $\mathcal{Q}$ corresponding to d_i binds and d_i ranks all the generators in $\mathcal{V}_{d_i}^*$ over v.*

In example 3.3, the following is a dominating solution (that we will interpret later):

$$z_{v_1}^* = 1; z_{v_2}^* = 1; z_{v_3}^* = 0, z_{v_4}^* = 0.$$

We can recover the corresponding matching x^* by setting $x^* := \mathcal{V} z^*$:

$$x^*(d_1, h_1) = 1; x^*(d_2, h_1) = 1; x^*(d_1, h_2) = 0; x^*(d_2, h_2) = 0.$$

Notice, in this case, the matching is integral. If x^* is integral, it will correspond to a stable matching. However, in general, x^* is fractional. In the next section, we provide an algorithm to convert x^* to an integral solution.

4 Algorithm

In the previous section, we showed how to obtain a fractional matching from a dominating solution. In particular, we let z^* be a dominating solution and set $x^* = \mathcal{V}z^*$. We show below how to round x^* into an integer $\bar{x}$ that satisfies (5-6) and almost satisfies (7).

4.1 Rounding

LEMMA 2. *Given x^*, there exists integral $\bar{x}$ such that*

- $x^*(d,h) = 0 \Rightarrow \bar{x}(d,h) = 0.$
- $\left\lfloor \sum_{h \in H} x^*(d,h) \right\rfloor \le \sum_{h \in H} \bar{x}(d,h) \le 1 \ \forall d \in D$
- $\left\lfloor \sum_{d \in D} x^*(d,h) \right\rfloor \le \sum_{d \in D} \bar{x}(d,h) \le k_h \ \forall h \in H$
- $\left\lfloor \sum_{d \in D_t^h} x^*(d,h) \right\rfloor \le \sum_{d \in D_t^h} \bar{x}(d,h) \le \left\lceil \sum_{d \in D_t^h} x^*(d,h) \right\rceil \ \forall t = 1, \dots, T_h, \ \forall h \in H$

Furthermore, $\bar{x}$ can be found by a polynomial time algorithm.

Lemma 2 shows that we can always round a matching x^* to $\bar{x}$ such that capacities at the hospitals are not violated and the number of doctors for each type is rounded either up or down to the closest integral number.[7] This is essentially the best integer solution that can be hoped for.

Proof. We show that the problem of finding $\bar{x}$ can be formulated as the problem of finding a feasible flow in a network, all of whose arc capacities are integral. Integrability of $\bar{x}$ follows immediately.

Introduce a source node σ, a sink node τ, one node for each $d \in D$, $h \in H$ and D_t^h. For each $d \in D$ there is an arc directed from σ to d with upper bound arc capacity of 1. For each d there is an arc directed to D_t^h if $d \in D_t^h$ *and* $x^*(d,h) > 0$ with upper bound arc capacity of

[7]This is similar to Theorem 3 in Budish et al. (2013).

1 and lower bound of $\left\lfloor \sum_{h \in H} x^*(d,h) \right\rfloor$. For each D_t^h there is an arc directed to h with upper bound arc capacity of $\left\lceil \sum_{d \in D_t^h} x^*(d,h) \right\rceil$ and lower bound arc capacity of $\left\lfloor \sum_{d \in D_t^h} x^*(d,h) \right\rfloor$. For each $h \in H$ there is an arc directed from h to τ with upper bound arc capacity of k_h and lower bound arc capacity of $\left\lfloor \sum_{d \in D} x^*(d,h) \right\rfloor$.

Note that x^* is a feasible flow in this network, so we know that a feasible integer flow exists.

□

4.2 Modifying α

Denote by $\bar{\mu}$ the matching associated with $\bar{x}$. Due to rounding, the proportionality constraints might be violated. We will need to change α to make $\bar{\mu}$ feasible. In particular, consider a group D_t^h.

- If in the fractional solution $\sum_{d \in D_t^h} x^*(d,h) = \alpha_t^h \sum_{d \in D^h} x^*(d,h)$, then let

$$\bar{\alpha}_t^h = \frac{\sum_{d \in D_t^h} \bar{x}(d,h)}{\sum_{d \in D^h} \bar{x}(d,h)}. \tag{10}$$

- If $\sum_{d \in D_t^h} x^*(d,h) > \alpha_t^h \sum_{d \in D^h} x^*(d,h)$ but $\sum_{d \in D_t^h} \bar{x}(d,h) < \alpha_t^h \sum_{d \in D^h} \bar{x}(d,h)$, then also let $\bar{\alpha}_t^h$ be as above. Otherwise $\bar{\alpha}_t^h = \alpha_t^h$.

With this, our main result is the following.

Theorem 4.1. *Given the fractional stable matching x^*, let $\bar{\mu}$ be the matching obtained from x^* via Lemma 2. Then $\bar{\mu}$ is feasible and stable for the instance* $(\{\succ_d\}_{d \in D}, \{\succ_h\}_{h \in H}, \{\bar{\alpha}^h\}_{h \in H})$.

The proof is given in Section 5. In the following, we show proximity bounds for the new matching.

4.3 Proximity Bounds

We can use Lemma 2 to quantify the closeness of $\bar{\mu}$ to x^*. By Lemma 2,

$$|\bar{\mu}(h)| \in \{\Big\lfloor \sum_{d\in D} x^*(d,h)\Big\rfloor, \Big\lceil \sum_{d\in D} x^*(d,h)\Big\rceil\}.$$

Thus, we never violate the capacity constraint of h. Furthermore, the rounding bound also implies that

$$||\bar{\mu}(h)| - \sum_{d\in D} x^*(d,h)| \leq 1 \ \forall h \in H.$$

By Lemma 2, $|\bar{\mu}(h) \cap D_t^h| \in \{\Big\lfloor \sum_{d\in D_t^h} x^*(d,h)\Big\rfloor, \Big\lceil \sum_{d\in D_t^h} x^*(d,h)\Big\rceil\}$.

$$\text{Hence} \quad ||\bar{\mu}(h) \cap D_t^h| - \sum_{d\in D_t^h} x^*(d,h)| \leq 1 \ \forall D_t^h.$$

In fact, when the proportionality constraint associated with D_t^h binds, we can say something more:

$$||\bar{\mu}(h) \cap D_t^h| - \alpha_t^h \sum_{d\in D} x^*(d,h)| \leq 1$$

because

$$|\bar{\mu}(h) \cap D_t^h| \in \{\Big\lfloor \alpha_t^h \sum_{d\in D} x^*(d,h)\Big\rfloor, \Big\lceil \alpha_t^h \sum_{d\in D} x^*(d,h)\Big\rceil\}.$$

Notice that the total number of doctors assigned to any h differs by at most 1 from the original fractional quantity. The same is true for the number of doctors of a particular type. The proportions, however, can behave quite differently. Using these proximity bounds it is straightforward to argue that

$$|\alpha_t^h - \bar{\alpha}_t^h| = |\alpha_t^h - \frac{|\bar{\mu}(h) \cap D_t^h|}{|\bar{\mu}(h)|}| \leq \frac{2}{1 + \sum_{d\in D} x^*(d,h)} \ \forall D_t^h.$$

Of course, if h were fully allocated under x^*, this bound would reduce to $\frac{2}{1+k_h}$. If the proportionality constraint for D_t^h binds, this bound improves to $\frac{1+\alpha_t^h}{1+\sum_{d\in D} x^*(d,h)}$. In all cases, the closeness of the realized proportions, $\frac{|\bar{\mu}(h)\cap D_t^h|}{|\bar{\mu}(h)|}$ to α_t^h, depend upon the size of $|\bar{\mu}(h)|$, the number of doctors matched to h. If $|\bar{\mu}(h)|$ is small, even small changes in the number of doctors assigned to h can have a large effect on the relevant proportions. If large, then a change in one doctor more or less will have a negligible effect on the relevant proportions.

5 Stability of $\bar{\mu}$

Recall that our algorithm starts from a dominating solution, z^*, which is a weight vector of the generators. The algorithm converts z^* to $x^* := \mathcal{V}z^*$, which is a fractional matching between doctors and hospitals. The solution x^* is then rounded to an integral solution $\bar{x}$. We denote $\bar{\mu}$ to be the corresponding matching.

We now show that $\bar{\mu}$ is stable with respect to $\bar{\alpha}$. We prove this by contradiction. Assume that it is not stable. We will construct a generator that is not dominated by z^*. Below we use the notation of $\mathcal{V}^*, \mathcal{V}_h^*$ defined in Remark 2.

A group D_t^h **reaches its lower bound** in x^* if the corresponding proportionality constraint binds, that is,

$$\sum_{d\in D_t^h} x^*(d,h) = \alpha_t^h \sum_{d\in D} x^*(d,h).$$

The following observations will be helpful in the proof.

Observation 1. *If a group D_t^h reaches its lower bound in x^*, then it also reaches its lower bound with respect to $\bar{x}$ and the modified $\bar{\alpha}$ defined in equation (10).*

Proof. Observation 1 comes directly from the definition of $\bar{\alpha}$ □

Observation 2. *If a group D_t^h reaches its lower bound in x^*, then for every $v \in \mathcal{V}_h^*$ and $d \in D_t^h$ such that $v(h,d) > 0$, $v(h,d) = \alpha_t^h$.*

Proof. Observation 2 comes from the way we construct the generators. In particular, for all generator $v \in \mathcal{V}_h^*$, if $v(h,d) > 0$, then $v(h,d) \geq \alpha_t^h$. Thus, if D_t^h reaches it lower bound in x^*, then there cannot be a $v \in \mathcal{V}_h^*$ such that $v(h,d)$ is strictly greater than α_t^h. □

Observation 3. *If d is a wait-listed doctor at h under $\bar{\mu}$, then, any generator in $\mathcal{V}_h$ that assigns d to h cannot be dominated via d.*

Proof. If d is assigned by $\bar{\mu}$ to a hospital h' such that $h \succ_d h'$, this means that there is a generator $v \in \mathcal{V}_{h'}^*$. This implies that any generator assigning d to h will be ranked above v. If d is unassigned under $\bar{\mu}$, it means that the constraint of d does not bind, that is, $\sum_{h\in H} x^*(d,h) < 1$. Hence the constraint corresponding to d in $\mathcal{Q}$ also does not bind. Thus, no generator can be dominated at this constraint. □

Proof of Theorem 4.1

Suppose $\bar{\mu}$ is not stable. This means that either h does not reach its effective capacity or there exists d_r currently matched with h that can be exchanged by a better doctor d_a who is on the wait list of h. There are 2 cases in which d_r can be replaced by d_a. They are either of the same type, or of a different type but d_r is not protected. We will construct a generator that is not dominated by z^*, which leads to a contradiction.

Case 1: h is not at its effective capacity under $\bar{\mu}$.

From Remark 1, this means that $\sum_{d\in D} \bar{x}(d,h) < k_h$. However, because of the rounding procedure, this implies that $\sum_{d\in D} x^*(d,h) < k_h$ Thus, no generator can be dominated at h. It remains to create a generator $v \in \mathcal{V}_h$ that is not dominated via any doctor. This will lead to a contradiction because z^* is a dominating solution.

Let $\{i_1,\ldots,i_k\}$ be the set of types that contain wait-listed doctors. Choose one wait-listed doctor from each type to be part of the generator v. Let they be $d_{i_1},..,d_{i_k}$. Also let $v(d_{i_1},h) = 1 - \sum_{t\neq i_1} \alpha_t^h$ and $v(d_{i_2},h) = \alpha_{i_2}^h, ..., v(d_{i_k},h) = \alpha_{i_k}^h$. By Observation 3, the generator that we are constructing cannot be dominated at $d_{i_1}, .., d_{i_k}$.

Denote the remaining set of types by $\{i_{k+1}, \dots, i_{T_h}\}$. These types do not contain any wait-listed doctor, because h is not at its effective capacity, according to Remark 1, their side constraints does not bind in the matching $\bar{\mu}$. According to Observation 1, this means that the side constraints of these types do not bind in the fractional solution x^*. Because of Observation 2, this means that for each type $t \in \{i_{k+1}, \dots, i_{T_h}\}$, there exists $v_t \in \mathcal{V}_h^*$ that assigns a doctor $d_t \in D_t^h$ to h with probability higher than α_t^h, i.e., $v_t(d_t, h) > \alpha_t^h$. Let d_t be part of the generator v, and let $v(d_t, h) = \alpha_t^h$. By the way the preference order is defined for doctors, d_t prefers this new generator to v_t. Thus, v cannot be dominated at any doctor. This contradicts the fact that z^* is a dominating solution.

Case 2a: d_r and d_a are of the same type.

Let $v_r \in \mathcal{V}_h^*$ be a generator that assigns d_r to h. Let v_a be the generator obtained from v_r by assigning d_a to h instead of assigning d_r to h with the same probability. Clearly, because $d_a \succ d_r$, v_a is ranked above v_r by h and all doctors of different types than d_a. Because of Observation 3 , v_a is not dominated at d_a. Thus z^* does not dominate v_a, a contradiction.

Case 2b: $d_a \in D_a^h$ and $d_r \in D_r^h$ are not of the same type and d_r is not protected under $\bar{\mu}$.

Because d_r is not protected under $\bar{\mu}$, in the fractional solution the side constraint of D_r^h does not bind (does not reach its lower bound). Among all the doctors d whose side constraints does not bind and $x^*(d, h) > 0$, let d_{min} be the least preferred doctor according to h. Assume $d_{min} \in D_{min}^h$. Clearly, $d_a \succ_h d_r \succeq d_{min}$. If d_a and d_{min} are of the same type, we return to Case 2a. Assume therefore that they are of different types.

Let $v_{min} \in \mathcal{V}_h^*$ be a generator that assigns d_{min} to h. Because $x^*(d_{min}, h) > 0$, such a v_{min} exists. There might be several such generators; if so, choose one with the highest probability of assigning d_{min} to h, i.e, the highest $v_{min}(d_{min}, h)$. We will construct $v_a \in \mathcal{V}_h$ by modifying v_{min} such that v_a is dominated by neither h nor any doctor.

a) v_a assigns d_a to h with probability $1 - \sum_{t \neq a} \alpha_t^h$. By Observation 3, v_a cannot be dominated via d_a.

b) Because the side constraint D_{min}^h does not bind in the fractional solution, there exists $v'_{min} \in \mathcal{V}_h^*$ that assigns a doctor $d'_{min} \in D_{min}^h$ to h with probability higher than α_{min}^h ($d'_m in$ and d_{min} can coincide). Let v_a assign d'_{min} to h with probability α_{min}^h. Thus, v_a will not be dominated at d'_{min}.

c) v_a assigns the same doctor in the remaining groups as in v_{min}, with probability α_t^h for group D_t^h. With this choice the sum of the components of v added up over the doctors will be 1.

The set of doctors assigned by v_a and v_{min} are different only in D_a^h and D_{min}^h. To compare v_a and v_{min}, we only need to compare these doctors. First, notice that $d_a \succ d_{min}$. Now, if $d'_{min} \neq d_{min}$, then $d'_{min} \succ_h d_{min}$ because of the choice of d_{min}. Thus, that h ranks the generators according to the lexicographical order; therefore, v_a is better than v_{min} because it replaces d_{min} with a better doctor. For the case $d'_{min} = d_{min}$, notice that v_a assigns d_{min} with probability α_{min}^h, which is less than the probability of v_{min}. Therefore h also prefers v_a to v_{min}. Hence v_a cannot be dominated via h.

Furthermore, the doctors breaks ties among generators according to h's lexicographical order v_a cannot be dominated via any doctor in the remaining groups.

Hence, we conclude that $v_a \succ_h v_{min}$ and cannot be dominated by z^*, which is a contradiction.

6 Lower Bounds and Upper Bound

In some cases, the proportion of individuals of a particular type matched to a school or hospital is constrained to fall within some interval. To accommodate this, we extend the earlier analysis to include both lower and upper bound proportionality constraints. Using the notation from prior sections, we consider the following constraints.

$$\alpha_t^h \cdot |\mu(h)| \leq |\mu(h) \cap D_t^h| \leq \beta_t^h \cdot |\mu(h)| \ \forall t = 1, \ldots, T_h, \text{ where } 0 \leq \alpha_t^h \leq \beta_t^h \leq 1, \sum_t \alpha_t^h \leq 1 \leq \sum_t \beta_t^h. \tag{11}$$

Call a matching that satisfies (11) **feasible.** If we choose $\beta_t^h = 1$ for all h and t, we recover (2). We maintain the same notation as before, and departures are noted as they arise.

We develop an algorithm to find a stable matching that slightly violates the proportionality constraints (11). The main result is in Theorem 6.2. We first define the notion of stability in Section 6.1. Section 6.2 describes the set of cone generators used in the algorithm presented in Section 6.3. The main proof to show that the matching we obtain by this algorithm is stable is given in Section 6.4.

6.1 Stability

The presence of upper and lower bounds on the relevant proportions requires a modification of the definition of a hospital's effective capacity with respect to μ. To see why, fix a hospital h and a subset $S \subset \{1, .., T_h\}$ of the types at that hospital. The upper bounds for all types in $\{1, .., T_h\} \setminus S$ induce a lower bound on the percentage of doctors whose type is in S. Specifically, the number of doctors with types in S needs to be at least a $1 - \sum_{t \notin S} \beta_t^h$ fraction of all the doctors assigned to h. That is,

$$|\mu(h) \cap (\bigcup_{s \in S} D_s^h)| \geq (1 - \sum_{t \notin S} \beta_t^h) \cdot |\mu(h)|. \tag{12}$$

Given a matching μ, if among the doctors in $\bigcup_{s\in S} D_s^h$, there are no wait-listed doctors, then, h cannot hope to increase the number of admitted doctors with types in S. Therefore, from (12) the effective capacity of h will be at most

$$\frac{|\mu(h) \cap (\bigcup_{s\in S} D_s^h)|}{1 - \sum_{t\notin S} \beta_t^h}.$$

This motivates the following extension of definition 2.2.

DEFINITION 6.1 (Effective Capacity). *Consider a feasible matching μ and a hospital h. Let T_0 be the set of types t, such that D_t^h contains no wait-listed doctor. Let*

$$bound_1 := \min_{t\in T_0} \frac{1}{\alpha_t^h}|\mu(h) \cap D_t^h|; \quad bound_2 := \min_{S\subset T_0} \frac{1}{1 - \sum_{t\notin S} \beta_t^h}|\mu(h) \cap \bigcup_{s\in S} D_s^h|.$$

The effective capacity of hospital h with respect to μ, denoted by k_h^μ, is $\min\{k_h, bound_1, bound_2\}$. If $T_0 = \varnothing$, $bound_1$ and $bound_2$ are set to infinity.

As before, when μ is clear from context we omit its mention when referring to a hospitals effective capacity.

REMARK 3. *k_h^μ is an upper bound on the number of slots that h can fill by accepting more wait-listed doctor without violating the side constraints. Because μ is feasible, it satisfies the capacity and the side constraints. Thus, it is clear that $|\mu(h)| \leq k_h^\mu$.*

From definition 6.1, if h is not at its effective capacity, $|\mu(h)| < k_h^\mu$, the following three statements hold.

1. *$|\mu(h)| < k_h$.*

2. *There is no $t \in T_0$ such that the lower bound proportionality constraint corresponding to D_t^h binds, that is, $|\mu(h)| = \frac{1}{\alpha_t^h}|\mu(h) \cap D_t^h|$.*

3. *There is no $S \subset T_0$, such that all upper bound proportionality constraints for types $t \notin S$ bind. That is, $|\mu(h)| = \frac{1}{\beta_t^h}|\mu(h) \cap D_t^h|$, for all $t \notin S$.*

We must also extend Definition 2.3:

Definition 6.2 (Protected and Surplus Doctors). *Given a feasible matching μ, a doctor of type t is protected at $h \in H$ with respect to μ if the lower bound proportionality constraint associated with D_t^h binds with respect to its effective capacity.*
A doctor of type t is surplus at h with respect to μ if the upper bound proportionality constraint associated with type D_t^h binds with respect to the hospital's effective capacity.

As before when μ is clear from context we omit the qualifier 'with respect to μ'.

As in Definition 2.3, if a type is protected (surplus) at h it means that h cannot be matched to fewer (more) doctors of this type without reducing the number of positions at h.

Now, consider a hospital h and two doctors $d_a \succ_h d_r$. Assume that d_r is currently matched with h, while d_a is wait-listed at h. This means that h has an incentive to exchange d_r for d_a. The definition of bilateral stability below allows for such a blocking coalition, but requires that if h does so, it will violate the side constraints. This means that h must either decrease the number of protected doctors or increase the number of surplus doctor. Specifically, we have the following definition.

Definition 6.3 (Bilateral Stability). *A feasible matching μ is called bilaterally stable if the following two conditions hold:*

1. *Every hospital is at its effective capacity, that is $|\mu(h)| = k_h^\mu \ \forall h \in H$.*
2. *For any $d_a, d_r \in D$ for which d_a is wait-listed for h, $\mu(d') = h$, and $d_a \succ_h d_r$, then d_a, d_r are of different types and either d_a is surplus or d_r is protected.*

The first condition does not permit a hospital to increase its intake. The second says permitting h to replace d_r with d_a will violate (11).

As in Section 2.1, we show that (bilateral) stability implies coalitional stability. A hospital's choice function in the presence of side constraints is defined next.

DEFINITION 6.4. *The choice function of h on a subset of acceptable doctors D^*, denoted $Choice_h(D^*)$, is the subset of D^* with largest cardinality that satisfies the capacity constraints of h and the proportionality constraints. If there are multiple such subsets, then $Choice_h(D^*)$ is the best one in the lexicographical order according to $\succ_h$.*

With this we have the following theorem.

THEOREM 6.1. *Let μ be a stable matching, then for any group of doctors D^* on the wait list of h, $Choice_h(\mu(h) \cup D^*) = \mu(h)$.*

The proof of Theorem 6.1 is analogous to that of Theorem 2.1, and is omitted.

6.2 Cone Generators

We take the same steps as before. The first is to determine the generators of (11). Fix a hospital $h \in H$ and focus on:

$$\alpha_t^h \cdot \sum_{d \in D} x(h,d) \leq \sum_{d \in D_t^h} x(h,d) \leq \beta_t^h \cdot \sum_{d \in D} x(h,d) \ t = 1, \ldots, T_h. \tag{13}$$

The generators are the extreme points of the system

$$\sum_{t=1}^{T_h} v(d_t, h) = 1, \ \alpha_t^h \leq v(d_t, h) \leq \beta_t^h \ \forall t = 1, \ldots, T_h. \tag{14}$$

It is easy to see that an extreme point of (14) can be determined using the following algorithm.

1. Select one doctor from each D_t^h and call it d_t.

2. Choose an ordering of the selected doctors, and call it σ.

3. Set $v(d_t, h) = \alpha_t^h$ for $i = 1, \ldots, T_h$.

4. In the order selected, increase the value of each $v(d_t, h)$ as much as possible (up to β_t^h) until the remaining mass of $1 - \sum_{t=1}^{T_h} \alpha_t^h$ is exhausted.

With this algorithm, consider a generator for hospital h. If we order the T_h non-zero components in the order that they are selected by the algorithm, they will be of the form

$$\beta_{i_1}^h, .., \beta_{i_k}^h, \gamma, \alpha_{i_{k+2}}^h, ..., \alpha_{T_h}^h,$$

where $\gamma = 1 - \beta_{i_1}^h - ... - \beta_{i_k}^h - \alpha_{i_{k+2}}^h - ... - \alpha_{T_h}^h$.

Denote the resulting extreme point by $\{v^\sigma(d,h)\}_{d \in D, h \in H}$. Keep in mind that it is possible for two distinct orderings to give rise to the same extreme point. For subsequent arguments it is useful to distinguish between the two and hence the need to record the order.

Definition 6.5. *A generator $v^\sigma \in \mathcal{V}_h$* **contains** *doctor $d \in D$ if $v^\sigma(d,h) > 0$. The* **order** *of a doctor d contained in generator $v^\sigma \in \mathcal{V}_h$ is the order of d in σ and is denoted $\sigma(d)$. The order of d is undefined if the generator does not contain d.*

Example 6.1. *Consider the example in Figure 1. Assume $\beta_1^{h_1} = \beta_2^{h_1} = \beta_3^{h_1} = .45$.*

We describe one generator of this system.

1. *Select $d_2 \in D_1^{h_1}$; $d_6 \in D_2^{h_1}$; $d_8 \in D_3^{h_1}$*

2. *Let σ be the order (d_6, d_2, d_8)*

3. *Set $v^\sigma(d_2, h_1) = 1/3$, $v^\sigma(d_6, h_1) = 1/3$; $v^\sigma(d_8, h_1) = 1/5$. The remaining coordinates are set to zero.*

4. *The remaining mass is* $1 - 1/3 - 1/3 - 1/5 = 2/15$ *is distributed in the order of* σ. *This gives* $v^{\sigma}(d_6, h_1) = .45, v^{\sigma}(d_2, h_1) = .35, v^{\sigma}(d_8, h_1) = 1/5 = .2$

We say the generator v^{σ} *contains* d_2, d_6, d_8. *The order of the doctors in this generator are* $\sigma(d_2) = 2$; $\sigma(d_6) = 1$ *and* $\sigma(d_8) = 3$.

6.3 Algorithm

Ranking of Columns in $\mathcal{AV}$

We consider the conic version of Scarf's lemma as in Section 3.3 The system $\mathcal{A} \cdot \mathcal{V} \cdot z \leq b$ is constructed in the same way as in Section 3.3. Each column of $\mathcal{A} \cdot \mathcal{V}$ corresponds to a generator v^{σ}, each row of $\mathcal{A} \cdot \mathcal{V}$ corresponds to a constraint for either a doctor or a hospital.

We now describe how each agent in $D \cup H$ *ranks* the columns of $\mathcal{AV}$. (We use the word "rank" to distinguish between the ordering over the columns of $\mathcal{AV}$ and $\mathcal{A}$.)

- h ranks two generators $v^{\sigma}, \bar{v}^{\sigma'} \in \mathcal{V}_h$ according to the lowest ranked doctor (according to $\succ_d$) contained in each of them. If the lowest ranked doctor of both v^{σ} and $\bar{v}^{\sigma'}$ are the same, say d_{min}, then break ties by comparing $\sigma(d_{min})$ and $\sigma'(d_{min})$. The lower the order, the less preferred. If they are equal, move to the second worst doctor contained in each and so on.

- d compares two generators $v^{\sigma}, \bar{v}^{\sigma'}$ that contain d according to the hospital that each assigns d to using $\succ_d$. If $v^{\sigma}, \bar{v}^{\sigma'}$ both assign d to the same hospital h, break ties by comparing $\sigma(d)$ and $\sigma'(d)$. Specifically, if $\sigma(d) > \sigma'(d)$, then v^{σ} is ranked above $\bar{v}^{\sigma'}$. If $\sigma(d) = \sigma'(d)$, then d uses h's ordering over the generators to break the tie.

Scarf's algorithm and rounding

We use the algorithm in Scarf (1967) to derive a dominating $z^* \in \mathcal{Q}$. Set $x^* = \mathcal{V}z^*$, and use Lemma 2 to round x^* into an integer $\bar{x}$ that satisfies (5-6) and almost satisfies (7). Let $\bar{\mu}$

be the corresponding matching.

Define $\bar{\alpha}$ and $\bar{\beta}$.

- If $\sum_{d\in D_t^h} x^*(d,h) = \alpha_t^h \sum_{d\in D^h} x^*(d,h)$, then, let

$$\bar{\alpha}_t^h = \frac{\sum_{d\in D_t^h} \bar{x}(d,h)}{\sum_{d\in D^h} \bar{x}(d,h)}. \tag{15}$$

- If $\sum_{d\in D_t^h} x^*(d,h) > \alpha_t^h \sum_{d\in D^h} x^*(d,h)$ but $\sum_{d\in D_t^h} \bar{x}(d,h) < \alpha_t^h \sum_{d\in D^h} \bar{x}(d,h)$, then let $\bar{\alpha}_t^h$ be as in (15). Otherwise $\bar{\alpha}_t^h = \alpha_t^h$.

- Similarly, if $\sum_{d\in D_t^h} x^*(d,h) = \beta_t^h \sum_{d\in D^h} x^*(d,h)$, then, let

$$\bar{\beta}_t^h = \frac{\sum_{d\in D_t^h} \bar{x}(d,h)}{\sum_{d\in D^h} \bar{x}(d,h)}. \tag{16}$$

- If $\sum_{d\in D_t^h} x^*(d,h) < \beta_t^h \sum_{d\in D^h} x^*(d,h)$ but $\sum_{d\in D_t^h} \bar{x}(d,h) > \beta_t^h \sum_{d\in D^h} \bar{x}(d,h)$, then also let $\bar{\beta}_t^h$ be as in (16). Otherwise $\bar{\beta}_t^h = \beta_t^h$.

An argument similar that in Section 4.3, yields the following proximity bounds for $\bar{\alpha}$ and $\bar{\beta}$:

$$|\alpha_t^h - \bar{\alpha}_t^h| = |\alpha_t^h - \frac{|\bar{\mu}(h) \cap D_t^h|}{|\bar{\mu}(h)|}| \le \frac{2}{1 + \sum_{d\in D} x^*(d,h)} \ \forall D_t^h,$$

and

$$|\beta_t^h - \bar{\beta}_t^h| = |\beta_t^h - \frac{|\bar{\mu}(h) \cap D_t^h|}{|\bar{\mu}(h)|}| \le \frac{2}{1 + \sum_{d\in D} x^*(d,h)} \ \forall D_t^h.$$

Our main result is

Theorem 6.2. *$\bar{\mu}$ is feasible and stable for the instance* $(\{\succ_d\}_{d\in D}, \{\succ_h\}_{h\in H}, \{\bar{\alpha}^h\}_{h\in H}, \{\bar{\beta}^h\}_{h\in H})$.

6.4 Stability of $\bar{\mu}$

Recall that $\mathcal{V}^* = \{v^\sigma \in \mathcal{V} : z^*_{v^\sigma} > 0\}$. For each hospital h, the set of generators in $\mathcal{V}^*$ associated with hospital h is denoted $\mathcal{V}^*_h$.

A group D^h_t **reaches its lower bound** in x^* if

$$\sum_{d\in D^h_t} x^*(d,h) = \alpha^h_t \sum_{d\in D} x^*(d,h).$$

Similarly, D^h_t **reaches its upper bound** in x^* if

$$\sum_{d\in D^h_t} x^*(d,h) = \beta^h_t \sum_{d\in D} x^*(d,h).$$

We use Observation 3 and the one below in the proof.

Observation 4. *Fix a hospital h and consider a partition of the set of types into 2 groups such that Group 1 contains $D^h_{i_1},...,D^h_{i_k}$ and group 2 contains $D^h_{i_{k+1}},...,D^h_{i_{T_h}}$ if for all doctors d in group 2 and all $v^\sigma \in \mathcal{V}^*_h$, $\sigma(d) \geq k+1$. Then, either each member of group 1 reaches its upper bound or each member in group 2 reaches its lower bound.*

Proof. Notice that, D^h_t reaches its lower bound in x^* if and only if for all generator $v^\sigma \in \mathcal{V}^*_h$ that contains $d \in D^h_t$, $v^\sigma(h,d) = \alpha^h_t$. Similarly, D^h_t reaches its upper bound in x^* if and only if for all generator $v^\sigma \in \mathcal{V}^*_h$ containing $d \in D^h_t$, $v^\sigma(h,d) = \beta^h_t$.

According to the algorithm producing the generators, if we order the T_h non-zero components in the order that they are selected by the algorithm, they will be of the form

$$\beta^h_{i_1},..,\beta^h_{i_k},\gamma,\alpha^h_{i_{k+2}},...,\alpha^h_{T_h},$$

where $\gamma = 1 - \beta^h_{i_1} - ... - \beta^h_{i_k} - \alpha^h_{i_{k+2}} - ... - \alpha^h_{T_h}$.

Because of the assumption that for all doctors d in group 2 and all $v^\sigma \in \mathcal{V}^*_h$, $\sigma(d) \geq k+1$, all doctors in group 2 is always selected after all doctors in group 1. Thus, either all the types in group 1 reach their upper bound, and if not, it is because the remaining mass of $1 - \sum_t \alpha_t^h$ is exhausted, and therefore all types in group 2 reach their lower bound. $\square$

Proof of Theorem 6.2

We are now ready to prove Theorem 6.2. Suppose, for a contradiction, that $\bar{\mu}$ is not stable. Let $d_a, d_r \in D$ be such that $\bar{\mu}(d_r) = h$, $\bar{\mu}(d_a) \neq h$ and $d_a \succ_h d_r$, i.e., d_a is wait-listed at h.[8] There are two cases to consider. In the first, h does not reach to its effective capacity. In the second, we can exchange d_r for d_a without violating (11).

Our goal is to construct a generator that is not dominated by z^*, which is a contradiction to the domination of z^*.

Case 1: h does not reach its effective capacity.

From Remark 3, this means that $|\bar{\mu}(h)| < k_h$. Because of the rounding does not violate hospital capacity, the capacity constraint at h does not bind in the fractional solution, that is $\sum_{d \in D} x^*(d,h) < k_h$. Thus, no generator can be dominated at h. It remains to create a generator $w^{\sigma'} \in \mathcal{V}_h$ that is not dominated via any doctor. This will lead to a contradiction because z^* is a dominating solution.

The first step is to choose σ'. Order the types so that all the types that contain a wait-listed doctor come first, and choose one wait-listed doctor from each of the types to be part of the generator. Let $\{i_1, \ldots, i_k\}$ be the set of these types. By observation 3, the generator that we are constructing cannot be dominated by the the constraints at these doctors.

Denote the remaining set of types by $\{i_{k+1}, \ldots, i_{T_h}\}$. If there is a doctor $d \in D^h_{i_{k+1}} \cup \ldots \cup D^h_{i_{T_h}}$ and a $v^\sigma \in \mathcal{V}^*_h$ such that $\sigma(d) \leq k$, then take this doctor to be the next in the order σ'. Hence, $\sigma'(d) > \sigma(d)$. Therefore, $w^{\sigma'}$ cannot be dominated via d. Repeat, until we cannot find such

[8] d_a, d_r denote for the doctor to accept and the doctor to reject, respectively.

a doctor. Without loss of generality suppose this happens at the first instance. According to Observation 4, either $D^h_{i_1}, ..., D^h_{i_k}$ reaches its upper bound in z^* or $D^h_{i_{k+1}}, ..., D^h_{i_{T_h}}$ reaches its lower bound in z^*. Because there is no wait-listed doctor in $D^h_{i_{k+1}} \cup ... \cup D^h_{i_{T_h}}$. Because of the rounding and modifying of α, this means that the corresponding constraints in the rounded matching $\bar{\mu}$ also bind. However, these types define the effective capacity at h, which contradicts the fact that h is not at its effective capacity.

By this argument we create a generator $w^{\sigma'}$ not dominated via any doctor. This contradicts the fact that z^* is a dominating solution.

Case 2: d_a can be exchanged for d_r.

- We argue that d_a and d_r are not of the same type. Suppose they are of the same type. Let $v^\sigma \in \mathcal{V}^*_h$ be a generator containing d_r. Let $w^\sigma \in \mathcal{V}_h$ be obtained from v^σ by shifting the probability weight from d_r to d_a but keeping the same order. Generator w^σ is ranked above v^σ by h and all doctors of types that differ from d_a and d_r. Moreover, because d_a is a wait-listed doctor, this generator cannot be dominated via d_a. Thus, this new generator is not dominated by z^*, a contradiction..

- Given that $d_a \in D^h_a, d_r \in D^h_r$ are not of the same type, we argue that either D^h_a reaches its upper bound, or D^h_r reaches its lower bound in z^*.[9] Suppose, for a contradiction, otherwise. Then, D^h_a has not reached its upper bound, and D^h_r has not reached its lower bound in z^*.

  Among all doctors d that have a type that has not reached its lower bound in z^*, and $x^*(d,h) > 0$ (doctor d_r is a member of this set), let d_{min} be the least preferred according to $\succ_h$. Let D^h_{min} be the set of doctors of the same type as d_{min}. Let $v^\sigma \in \mathcal{V}^*_h$ be a generator containing d_{min} such that d_{min}'s order, $\sigma(d_{min})$, is as small as possible.

[9] Because of the rounding procedure, and the modifying of α-s, this implies that either d_a is at surplus or d_r is protected at the rounded matching $\bar{\mu}$, with the modified $\bar{\alpha}$-s, $\bar{\beta}$-s. This is what we need to prove.

Such a generator exists because $x^*(d,h) > 0$.

Claim 1. *d_{min}, d_a are of different types; furthermore, if $d'_a \in D^h_a$ is contained in a generator $v^{\sigma'}$ (d'_a may be the same as d_a), then, $\sigma(d_{min}) > \sigma(d'_a)$.*

Proof. If d_{min} and d_a are of the same type, we could, in v^σ, shift the probability weight from d_{min} to d_a. This produces a generator that is not dominated via h because $d_a \succ_h d_r \succeq_h d_{min}$. It is clearly not dominated via d_a. Finally, it is not dominated via any doctor other than $\{d_a, d_{min}\}$ in the two generators, who will face a tie and break it in h's favor.

If σ orders d_{min} before the type of d'_a, i.e., $\sigma(d_{min}) < \sigma(d'_a)$, then switch the order of these two types, and if $d'_a \neq d_a$, shift the probability weight from d'_a to d_a. This new generator is not dominated via d_a because of Observation 3. Second, because we have switched the order of d_{min} and d'_a, this new generator is not dominated via d_{min}. Third, because $d_a \succ_h d_r$ for all other doctors and for h, the new generator is ranked above v^σ. Therefore, it cannot be dominated. $\square$

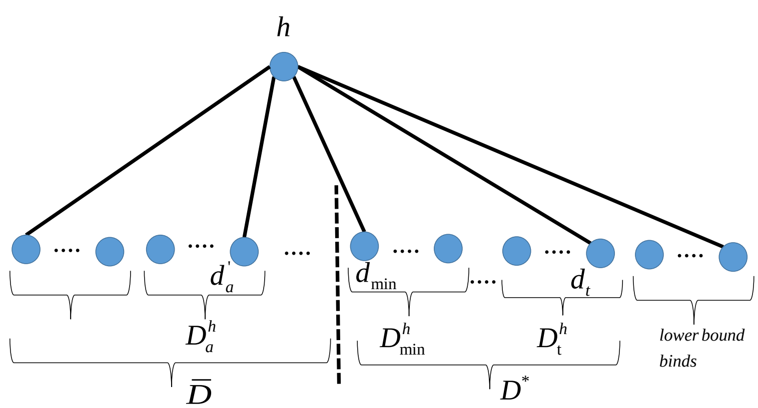

Figure 4: The generator v

Let D^* be the set of doctors who belong to types that have not reached their lower bounds in z^*, and their order in v^σ is at least the order of $\sigma(d_{min})$. See Figure 4.

Because of Claim 1, $D_a^h \cap D^* = \varnothing$.

Suppose, among the doctors in D^*, there is a $d_t \in D_t^h$ whose order under a different generator $\bar{v}^{\sigma'} \in \mathcal{V}_h^*$ is no larger than $\sigma(d_{min})$. Notice that d_t could be of the same type as d_{min}, but $d_t \neq d_{min}$ because d_{min} is the least preferred under $\succ_h$.

Create a new generator from $\bar{v}^{\sigma'}$ by switching the order of D_t^h, and D_{min}^h, and let d_t be part of this new generator (if d_t, d_{min} are the same type, replace d_{min} with d_t). The new generator is not dominated via d_t because d_t ranks it above $\bar{v}^{\sigma'}$. It is also ranked above v^σ by h, because d_{min} has a higher order, and thus is also ranked higher by all other doctors because they break ties according to $\succ_h$. Hence, this new generator is not dominated.

We are left with the case that the order of each doctor in D^* in every generator in $\mathcal{V}_h^*$ is at least $\sigma(d_{min})$. This means that for all generators in $\mathcal{V}_h^*$, doctors in D^* are ordered after $\bar{D}$, where $\bar{D}$ is the set of doctors whose types are ordered before D_{min}^h under σ. Similar to the argument in Observation 4, this means that either $\bar{D}$ reaches its upper bound, or D^* reaches its lower bound. However, this is impossible because $D_{min}^h \in D^*$ was chosen such that it does not reach its lower bound, and $D_a^h \in \bar{D}$ is assumed to not reach its upper bound.

This concludes the proof.

7 Conclusion

It is common to require that a matching satisfy a variety of distributional goals. These are sometimes expressed as lower or upper bounds on the proportion of agents of a particular type being matched. This paper is the first that we are aware of to address this problem. It uses a novel extension of Scarf's lemma to identify a stable matching that approximately satisfies such proportionality constraints. In addition, ex-post bounds on the deviation between the realized and desired proportions are provided.

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