Maximize the Efficiency of Healthcare Matching: a Simple Modification

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1 Introduction

In the earlier stage of COVID-19, the allocation of healthcare is a tricky problem even though all these stuffs are produced in an unprecedented speed. The scarcity of healthcare in the early stage is linked to market design problem self-evidently. There are so many standards need to consider: the ethics value, the priority and the fairness as we did in the affirmative actions. Agencies have developed a series of baselines for the public health issue. Specifically, (1) the fair allocation to the groups of people with different gender, race and age; (2) maximizing the welfare of the society; (3) respect people who have done great contribution before. After respecting these protocols, there are a series of influential research work ongoing and many agencies have adopted their advice. Traditional mechanism is priority system, for example, 2018 US Centers for Disease Control Vaccine Allocation guideline gives the definitions of four types of priority (CDC, 2018)

(1) *Providing homeland and national security*, (2) *Providing health care and community support services*, (3) *Maintaining critical infrastructure*, and (4) *being a member of the general population*. Another priority orders are given by an objective scoring method, resulting in a priority point system. This have been implemented in the allocation ICU beds and ventilators. Also, this is used in other similar allocation problem like registered system in some cities of China. No matter what kind of rationing system it is about, one common issue in many debates is that they neglect some other important elements that are related to lives Akbarpour et al. [2021].

Related Literature Therefore, a series of research try to balance different values in the healthcare rationing. The pioneering work of Pathak et al. [2021] gives a baseline framework about allocation based on several primary axioms. And their approach has been recommended or adopted by various organizations including the NASEM and endorsed by medical researcher (Emanuel et al. [2020]; Sönmez S [2020]; Pathak PA [2021]). In the follow-up work,

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Grigoryan [2021] considers optimal approaches for variants of the problem with matching effectiveness and minimal cost-flow. He built on the ideas of Pathak et al. [2021] by introducing a match quality term to the allocation model, leading to a mechanism for allocating vaccines to different groups of agents in ways that maximize group-specific efficacy while respecting prioritization goals. In another thread of mechanism design literature, Akbarpour et al. [2021] proposes a method of incorporating various unobservable features compared to former researches.

In contrast to the papers on healthcare rationing discussed above, I simplify the assumption that agents with specific type. Compared to Grigoryan [2021] and Abdulkadiroğlu and Grigoryan [2021] I dropped the specific type restrictions for agents (so-called soft-reserve system) and consider heterogeneous preference for healthcare. They consider a matching system with heterogeneous types of agents and homogenous preference for different kinds of healthcare. Also, compared to Pathak et al. [2021], In order to maximize the matching size and respect the baseline priority as much as possible, I use a matching order that is different from Deferred Acceptance order in their paper. My algorithm only considers the most simple measurement of efficiency-the size of the matching and meet the axioms promoted by Pathak et al. [2021] at the same time.

2 The Model

Allocation problem has been put into the framework of two-side matching. I refer similar framework of Pathak et al. [2021] and Abdulkadiroğlu and Grigoryan [2021]. There is a finite set of agents $\mathcal{A}$. The matching is a mapping $\mathcal{M} : 2^{\mathcal{A}} \to 2^{\mathcal{A}}$ such that $\forall A \subseteq \mathcal{A}, \mathcal{M}(A) \subseteq \mathcal{A}$, and $|\mathcal{M}(A)| \leq q$. Applicants are also categorized into different set of types $\mathcal{T}$ by mapping $\mathcal{C}$ defined by $\{t \in \mathcal{T} : \mathcal{C}(a) = t, a \in \mathcal{A}\}$. For the convenience I define the notion $A_t : \{a \in \mathcal{A} : \mathcal{C}(a) = t, t \in \mathcal{T}\}, a_t \in A_t$. Also, quota q can also be divided into different categories of $\mathcal{T}$ such that $\sum_{t\in\mathcal{T}} q_t = q$ and a priority ranking $\geq_t$ which is a preorder on $\mathcal{A} \cup \{\emptyset\}$. The baseline ordering of allocation is π.

The matching $\mu \in \mathcal{M}$ should follow these three axioms, which is the minimum requirement for a reserved-quota matching system:

Axiom 1. *A matching $\mathcal{M}$ complies with eligibility condition if $\forall a \in \mathcal{A}$ and $\forall t \in \mathcal{T}$,*

$$\mu(a) = t \to a \geq_t \emptyset$$

Axiom 2. *A matching $\mu \in \mathcal{M}$ is non-wasteful if $\forall a \in \mathcal{A}$ and $\forall t \in \mathcal{T}$,*

$$a \geq_t \emptyset \text{ and } \mu(a) = \emptyset \to \left|\mu^{-1}(t)\right| = r_t$$

if t is eligible for a.

Axiom 3. *A matching $\mu \in \mathcal{M}$ respects priorities within each category $t \in \mathcal{T}$ if for any $a, a' \in \mathcal{A}$,*

$$\mu(a) = t, \quad \mu\left(a'\right) = \emptyset \rightarrow \quad a \geq_c a'$$

Besides these three conditions, it should follow maximizing-efficiency condition.

Definition 1. *A matching $\mu \in \mathcal{M}$ is maximizing-efficiency if it has the most size among all matching meets Axiom* 1.

Definition 2. *A matching $\mu \in \mathcal{M}$ is strategy-proofness if $\mu(a) = \emptyset$ and $\mu'(a) = \emptyset$ for any other priority represent a.*

My target is to explore an algorithm to meet three axioms and one of two of definitions. In many real-life application of reserves allocations, we cannot use baseline order directly considering the affirmative actions. Diversity, equity and inclusiveness are also the consideration of allocation system. A typical case is education, the racial minorities and other marginal community are also shut out of the system, which is also true for health care allocation system. This is the incentive to introduce a kind of unreserved and beneficiary group.

Definition 3. ***Beneficiary-type and unreserved-type***. *If one category is not necessary eligible for any agent with heterogeneous priory belongs to which namely*

$$\forall t \in \mathcal{T} \quad with \quad \geq_t$$

And another type $u \in \mathcal{T}$ is eligible for any types of agents endowed with baseline order. That is

$$\geqslant_u = \pi$$

As the definition of Pathak et al. [2021], there are two kinds of reserves:

(i) Soft reserves: for any type of agents $a \in \mathcal{A}$, and any category of health care q_t, individuals are eligible for all categories, i.e.

$$a \geq_t \emptyset$$

(ii) Hard reserves: for category $t \in \mathcal{T} \backslash \{u\}$, all the beneficiary agents of type t are eligible $a_t \geq_t \emptyset$ but $\emptyset \geqslant_t a_{t'}$ if $t' \neq t$

The sequence of unreserved category matters for the results of the allocation. The results are totally different if we reverse the order of unreserved and reserved healthcare. I use a simple example to illustrate the difference between these two system but I mainly consider a simple case of software reserve system.

Example 1. *Consider a set of agents $\mathcal{A} = \{a_1, a_2, a_3\}, \mathcal{T} = \{t_1, t_2, u\}, q_1 = 1, q_u = 1, \mathcal{C}(a_1) = t_1, \mathcal{C}(a_2) = t_2, \mathcal{C}(a_3) = t_2$. Baseline order $\pi = (1, 2, 3)$.*

If it is a hard-reserve system:

Case 1. *If we tackle unreserved stuffs firstly, the allocation results will be*

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ u & \emptyset & \emptyset \end{pmatrix}$$

Case 2. *If we tackle beneficiary category firstly, which will become*

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ q_1 & u & \emptyset \end{pmatrix}$$

If it is a soft-reserve system:

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In example 1, we can see the difference in soft-reserve system and hard-reserve system is there is the beneficiary category is allocated to the agent belong to which. But in case 1 of hard-reserved system, there is no exact beneficiary class is assigned to right agents. In sight of this, we can introduce another notion maximum beneficiary matching. So, in terms of maximizing the efficiency we only consider soft-reserve system in this work.

2.1 No unreserved healthcare, $q_u = 0$

Firstly, we consider the case that $q_u = 0$.

Example 2. *If agents set $\mathcal{A} = \{a_1, a_2, a_3\}$, $a_1 \in t_1, a_2 \in t_2, a_3 \in t_2$. Baseline order $\pi = (1, 2, 3)$. Priority of t_1 is $a_1 \geq a_3 \geq \emptyset$ and priority of t_2 is $a_1 \geq \emptyset$ If we use the baseline order, the matching results will be*

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ t_1 & \emptyset & \emptyset \end{pmatrix}$$

And another possible matching size which is better than this

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ t_2 & \emptyset & t_1 \end{pmatrix}$$

In sight of this we introduce an algorithm called *inverse-maximizing matching algorithm*.

Algorithm 1. ***Inverse-maximizing matching algorithm***
Step 0. *Let* $I_0 = \emptyset, \mathcal{M}_0 = \text{argmax}_{\mu \in \mathcal{M}} \left|\mu^{-1}(\mathcal{A})\right|$
Step 1(k). *Given the baseline order* π,

$$a_1 \ \pi \ a_2 \ \pi \ a_3 \ \dots \ \pi \ a_{|\mathcal{A}|}$$

Process agent $a_{|\mathcal{A}|-(k-1)}$ *if* $a_{|\mathcal{A}|-(k-1)} \notin I_0$. *Consider the subgroup with excluding* $\left\{a_{|\mathcal{A}|-(k-1)}\right\}$, *in order to avoid priority violation, agents that are with lower priority* $\cup_{t \in \mathcal{T}} V_t$, $V_t = \{a_t : a_t$ *has lower priority than* $a_{|\mathcal{A}|-(k-1)}\Big\}$ *also excluded. If*

$$\mathcal{M}_k = \text{argmax}_{\mu \in \mathcal{M}} \left|\mu^{-1}\left(\mathcal{A} \backslash \left(\left\{a_{|\mathcal{A}|-(k-1)}\right\} \cup \left(\cup_{t \in \mathcal{T}} V_t\right) \cup I_{k-1}\right)\right)\right|$$

and $\mathcal{M}_k \subseteq \mathcal{M}_{k-1}$, *then define*

$$I_k = \left\{a_{|\mathcal{A}|-(k-1)}\right\} \cup I_{k-1} \cup \left(\cup_{t \in \mathcal{T}} V_t\right)$$

Otherwise

$$I_k = I_{k-1}, \quad \mathcal{M}_k = \mathcal{M}_{k-1}$$

This step will stop if all agents $\mathcal{A}$ *have been considered.*
Step k+1, *Choose a matching* $\mu \in \mathcal{M}_k$

Theorem 1. ***(Existence)*** *Inverse-maximizing matching algorithm will generate a set of maximize matching that meet requirements Axiom 1, Axiom 2, Axiom 3.*

Proof. I use induction to prove this. Assume $\mathcal{M}_k$ meets Axiom 1, Axiom 2, Axiom 3. Because $\cup_{t \in \mathcal{T}} V_t$ has also been excluded in the process of constructing $\mathcal{M}_k$, which means all agents in $\mathcal{A}_{k+1} = \mathcal{A} \backslash \left(\left\{a_{|\mathcal{A}|-(k-1)}\right\} \cup \left(\cup_{t \in \mathcal{T}} V_t\right) \cup I_{k-1}\right)$ can construct matching $\mathcal{M}_{k+1} \subseteq \mathcal{M}_k$ such that is also eligible, i.e. $\forall a \in \mathcal{A}_{k+1}, \mu \in \mathcal{M}_{k+1}, \mu(a) \in \mathcal{T}, a >_{\mu(a)} \emptyset$. Also, if matching $\mu \in \mathcal{M}_k, \forall a, a' \in \mathcal{A}_k, \mu(a) \in \mathcal{T}, \mu\left(a'\right) = \emptyset, a >_{\mu(a)} a'$. For $\mu' \in \mathcal{M}_{k+1}$, if $a' \in V_t = \{a_t : a_t$ has lower priority than $a_{|\mathcal{A}|-(k-1)}\Big\}$, then the allocation results will not be affected consider all agents who have lower priority have been excluded. In another case, $a' \notin V_t$, then $\forall a \in V_t$ such that $a' \ \pi \ a$. And the matching for a will also not be affected. If $a \in \mathcal{A} \backslash \mathcal{M}(\mathcal{A}), \mu(a) = \emptyset$, it implies $\left|\mu^{-1}(\mathcal{C}(a))\right| = q_{\mathcal{C}(a)}$. Let the set of $\mathcal{M}_w \subseteq \mathcal{M}, \mathcal{M}_w$ is the set of non-wasteness matching. If matching μ is a maximized matching, then any other matching $\mu' \subseteq \mathcal{M}_w \subseteq \mathcal{M}$, the size of matching is less than maximized matching. Assume an agent $a^* \in \mathcal{A} \backslash \mathcal{M}(\mathcal{A})$ can formalize another matching such that $\left|\mu^{-1}\left(\mathcal{C}\left(a^*\right)\right)\right| = q_{\mathcal{C}(a^*)}$. According to assumption, there will be at least two agents $a_1, a_2 \in \mathcal{M}(\mathcal{A})$ will be excluded, then types $\mathcal{C}\left(a_1\right), \mathcal{C}\left(a_2\right)$ are wasted. On the other hand, if matching μ makes $\mathcal{C}\left(a^*\right)$ wasted, then another matching μ'' can be constructed and the size of which is larger than μ. It contradicts the assumption. ■

Remark 1. *Maximizing condition prescribes a stronger condition than non-wasteful condition.*

I have proved the existence of the matching μ, and a natural question is the uniqueness of the matching generated by the algorithm.

Proposition 1. *(Uniqueness and Respect Priority) The excluding set I_k is unique and matching $|\mu| = |\mathcal{A}| - |I_k|$. And the matching is without justified envy.*

Proof. Assume the $|\mu| < |\mathcal{A}| - |I_k|$. This means there exist $a_t \in \mathcal{A}_k$ such that $\mu(a_t) = \emptyset$. If $I_{k+1} = I_k \cup a_t$, the matching is not affected. This contradicts the processing of algorithm. If $\mu(a_t) = \emptyset, \mu(a_t') = t$ and $a_t \geq_t a_t'$, then exclude and let $a_t \in I_{k+1}$. In this case a Pareto optimal matching with respect the priority can be constructed. The size of matching $|\mu| = |\mathcal{A}| - |I_k|$. But it contradicts the formulation of matching μ because a_t will be excluded with regards to the baseline order π. ∎

Another important issue in matching design problem is if agents can manipulate their preference to change the results of the matching. Non-bossiness (Satterthwaite and Sonnenschein [1981]) prescribes this nature. It says that whenever a change in an agent's preferences does not cause a change in his assignment, it should not cause a change in anybody else's assignment: thus, the entire allocation should remain the same. I consider a special case in this problem: agents can declare they are ineligible to a type of healthcare.

Definition 4. ***Non-bossiness and quasi non-bossiness*** *If any agent $a \in \mathcal{A}$ with preference $t \geq_a \emptyset$ show a wrong priority order π', and it will never affect the matching of $a' \in \mathcal{A} \backslash a, \mu'(a') = \mu(a'), \mu'$ is generated by the fake preference of a.*

Proposition 2. *Inverse-maximizing matching algorithm is quasi non-bossiness and strategyproofness.*

Proof. Given the baseline ordering π, suppose $(1, 2, \ldots |\mathcal{A}|)$. Assume a_n is in the set of I, and let $I_k^n = \{a \in I_k : a_n \pi a\}$ i.e. agents that have lower priority than a_n. If a_n hesitate her preference to declare she is not eligible to $\mu(a_n) \in \mathcal{T}$. To this end, we need to prove $I^n = I^{n'}$. This means we need to prove $\forall a_i \in I^n, a_i \in I^{n'}$. If in step k, a_i is considered in this step and generate excluding set I^i. And if $a_i \in I^n$, the matching μ is generated by I^n. And then for $I^{n'}$, for all agents $a \in I^n \backslash \{a_i, a_n\}$, the priorities that are lower than a_i are still the same. μ is also feasible matching. Otherwise, if $a_i \in I^{n'}, \mu$ is also a feasible matching for $a_i \in I^n$. Now prove the strategyproofness. Suppose a_n is unmatched in matching μ, this is equivalent to $a_n \in I_k^n$ and needs to prove $I_k^n = I_k^{n'}$, which has been proved before. ∎

2.2 Consider unreserved health care, $q_u \neq 0$

In this section, I consider another case $q_u \neq 0$. And consider all priorities of $t \in \mathcal{T}$ are homogeneous. According to Example 1, I give following definitions.

Definition 5. ***Maximum Beneficiary Matching*** *The set of beneficiary matching is all the agents that are matched to the beneficiary categories. So the matching μ should be the matching gotten from the maximum of the set.*

$$\mu \in \operatorname{argmax}_{v \in \mathcal{M}} \left| \cup_{t \in \mathcal{T} \setminus \{u\}} \left(v^{-1}(t) \cap A_t \right) \right|$$

Consider the certain policy sequence of allocating unreserved and beneficiary categories, we can also give the definitions of **Minimum-guarantee** and **Over-and-Above** (Blakeney [1964])

Definition 6. ***Minimum-guarantee***. *Baseline order is π. If one agent $a \in \mathcal{A}$ is eligible for a beneficiary category $t \in \mathcal{T}$, and matching $\mu \in \mathcal{M}$ implies that $\mu^{-1}(t) \leq q_t$. Then $\mu(a) = t$. Otherwise $\mu(a) = u$ if $\mu^{-1}(u) \leq q_u$.*

Definition 7. ***Over-and-Above***. *Baseline order is π. If $\mu^{-1}(u) \leq q_u$ and a is eligible for certain $t \in \mathcal{T}, \mu^{-1}(t) \leq q_t$. In the two cases we match a to t. Otherwise, we fill up the rest of categories: for each $t \in \mathcal{T}$, the highest $\min\{q_t, |N_t|\}$ agents are allocated to t.*

Algorithm 2. ***Inverse Smart Reserving Matching***
Fix the parameter n is the number of reserved unite to be processed and $n \leq q_u$ and other reserved unreserved healthcare will be processed at the end of the algorithm. Iteratively construct the agents set

$$\mathcal{A}_0^u \subseteq \mathcal{A}_1^u \subseteq \mathcal{A}_2^u \ldots \subseteq \mathcal{A}_{|\mathcal{A}|}^u$$

$\mathcal{A}_i^u$ where $i \leq |\mathcal{A}|$ is the set of agents to allocated to match unreserved agents and the order of consideration is baseline order π. And series

$$\mathcal{A}_0 \subseteq \mathcal{A}_1 \subseteq \mathcal{A}_2 \ldots \subseteq \mathcal{A}_{|\mathcal{A}|}$$

decides the agents matched to beneficiary units. And the series generates the matching sequence $\mathcal{M}_0 \supseteq \mathcal{M}_1 \supseteq \mathcal{M}_2 \ldots \supseteq \mathcal{M}_{|\mathcal{A}|}$.
Step 1. *Let*

$$\mathcal{A}_0^u = \emptyset, \quad \mathcal{A}_0 = \emptyset$$

Step 2(k) *Consider 3 cases:*
Case 1. *If $a_k \in \mathcal{A}_k^u$, and construct*

$$\mathcal{M}_k = \{\mu \in \mathcal{M}_{k-1} : \mu(a_k) = u\}$$

And

$$\mathcal{M}_{k-1} = \operatorname{argmax}_{\mu \in \mathcal{M}_{k-2}} \left| \cup_{t \in \mathcal{T}} \left(\mu^{-1}(t) \cap A_t \right) \right| = \operatorname{argmax}_{\mu \in \mathcal{M}_0} \left| \cup_{t \in \mathcal{T}} \left(\mu^{-1}(t) \cap A_t \right) \right|$$

Case 2. *If $a_k \in \mathcal{A}_k$, and construct*

$$\mathcal{M}_{k,t} = \{\mu \in \mathcal{M}_{k-1} : \mu(a_k) = t\}$$

And there exist $t \in \mathcal{T}$ such that $|\mathcal{M}_{k,t}| = \operatorname{argmax}_{\mu \in \mathcal{M}_0} \left|\cup_{t \in \mathcal{T}} \left(\mu^{-1}(t) \cap A_t\right)\right|$.
Case 3*: if 2 conditions above cannot be met keep the set same as former step*

$$\mathcal{A}_k^u = \mathcal{A}_{k-1}^u$$
$$\mathcal{A}_k = \mathcal{A}_{k-1}$$

Step 3*. Use inverse-maximizing rule to allocate all of remaining agents to beneficiary category.*
Step 4*. Allocate remaining unreserved categories according to the baseline order π.*

Proposition 3. *Inverse Smart Reserving Matching algorithm generates a set of maximize matching that meet requirements Axiom 1, Axiom 2, Axiom 3.*

Proof. Axiom 1, Axiom 2 are self-evident for the generation of the algorithm. Next step is to prove the Axiom 3. Because of unreserved units' priority is same as baseline order π, if there exist $\mu(a_t) = \emptyset$ and $\mu(a_t') = u$ but $a_t \geq_u a_t'$. In this case, according to the construction of algorithm, a_t will be considered firstly and if $\mu(a_t) = \emptyset$ then $\mu(a_t') = \emptyset$, which contradicts the assumptions. And for beneficiary units allocations, it follows Theorem 1.

■

Proposition 4. *Inverse Smart Reserving Matching algorithm is quasi non-bossiness and strategyproofness.*

Proof. Consider several cases:
Case 1. The first step of the algorithm is to allocate part of unreserved units. In the true case, agent a_n will not be incorporated into the set $\mathcal{A}_k^u$ because that cannot generate maximum matching. On the other hand, if a_n tells false priority to any $t \in \mathcal{T} \backslash \{u\}$, consider priority of any t will not be affected by agent $a \in \mathcal{A}$. So misrepresentation will not change the fact that it cannot generate maximum beneficiary matching. Also, if a cannot be considered into unreserved group, it means agents who have higher priorities have used up the unreserved units.
Case 2. The second step of the algorithm is to allocate beneficiary units. It has been proved before.
Case 3. The last step is to allocate unreserved units have not been allocated in step 1. If a isn't matched to the second part unreserved units, then priority lower than a cannot be matched. And the misrepresentation of a cannot affect the matching of the first two sets. So a cannot be matched to the set of unreserved units. ■

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