Algorithmic Waste Reduction

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ABSTRACT

Motivated by a desire for waste reduction through surplus redistribution, we explore the paradox of overproduction of resources that are wasted at several levels of the supply chain and the concurrent lack of access to, in most cases, overproduced basic resources by low income socioeconomic classes to whom resource access is normally only available through donation centers. To that end, we contrast two surplus redistribution solutions to this paradox. (1) Local independent donations between producers and donation centers. (2) Redistribution by way of a global redistributor (what we will call a core redistributor) who collects donations from all available producers and redistributes the surplus to all donation centers respective of their demanded quantities. We mathematically show that an optimal allocation of the surplus that minimizes waste and maximizes social welfare is only possible with a core redistributor. As this is a deeply social and economic problem rather than mathematical, we also qualitatively study two cases; (1) food waste and food insecurity in the UK, and (2) Los Angeles County's project RoomKey: a pandemic effort to house covid-vulnerable unhoused persons in vacant hotels and motels. Both case studies give more support for a core redistribution as a solution to waste from overproduction and lack of access to essential resources.

CCS CONCEPTS

• **Theory of computation** → **Algorithmic mechanism design**; • **Applied computing** → **Supply chain management**.

KEYWORDS

waste, surplus redistribution, core allocation,algorithmic decision making

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1 INTRODUCTION

In many resource industries within capitalist economies today, a large amount of surplus is created from overproduction [Fletcher 2011; Kettell 2006; Malikane 2017; Messner et al. 2021; Pouch and Trouvé 2018]. This surplus contributes to the massive global waste amounts; with annual estimates of 931 million tonnes of food wasted in 2019 (17% of the global food production) [Hamish Forbes WRAP], >92 million tonnes of textile waste (two thirds of this ends up in landfills) [Niinimäki et al. 2020; Shirvanimoghaddam et al. 2020],>50 million tonnes of electronic waste [Awasthi and Li 2019; Nithya et al. 2021], not to mention other resources whose waste is hard to track and quantify. For example, it is not clear how many hotels and motels are wasted annually, or how much clean water and pharmaceutical waste is generated in affluent communities around the world.

In the same capitalist economies, however, the income gap between the poorest and wealthiest grows larger every day [Hoffmann et al. 2020; Mijs 2021; Oronce et al. 2020; Patel et al. 2018; Solt 2020] (see figure 1 for the income gap growth in China, Russia, UK, and USA since 1971). This wide separation of economic classes continues to marginalize low income communities to a reality with limited access to essential resources [Couture et al. 2019; Dustmann et al. 2018; Khullar and Chokshi 2018]. This is evident from the gentrification seen in most major cities across the globe [Jover and Díaz-Parra 2020; Lee 2018; López-Morales et al. 2021; López-Morales 2015; Richardson et al. 2019; Visser 2019; Zhang et al. 2020]. While there is an overproduction of resources, there is a lack of access to those resources by the low income classes that cannot afford the costs [Blake 2019; Purdam et al. 2016; Thapa Karki et al. 2021]. This systemic failure is most evident in times of natural disasters/emergency situations during which the more affluent communities have an over-supply of resources while marginalized communities experience scarcities. A quick example is the response in Puerto Rico after Hurricane Maria compared to Texas and Florida after Hurricane Harvey and Irma [Willison et al. 2019].

There are many issues that lead to the creation of global waste, most of which arise from consumer behavior at the household level [WRAP 2021a,b]. However, there is still a considerable amount of surplus created within the supply chain that can be redistributed to those that lack access to the surplus resources [WRAP 2021a,b]. This research, therefore, highlights the structural mismatch (shown in figure 2) from which surplus is created and consequentially proposes an algorithmic solution for the redistribution of these over-produced resources to those without access to them. The solution presented here aims to minimize the cost of redistribution for the producers, minimize waste from over-produced resources (maximize utility for the redistributors), while also maximizing welfare for those that demand but have no access to the over-produced resources.

1.1 Literature Review

There is a long history of using algorithmic mechanism design towards solving social problems. Matching or allocation mechanisms are usually either one or two-sided, offline or online, with agents

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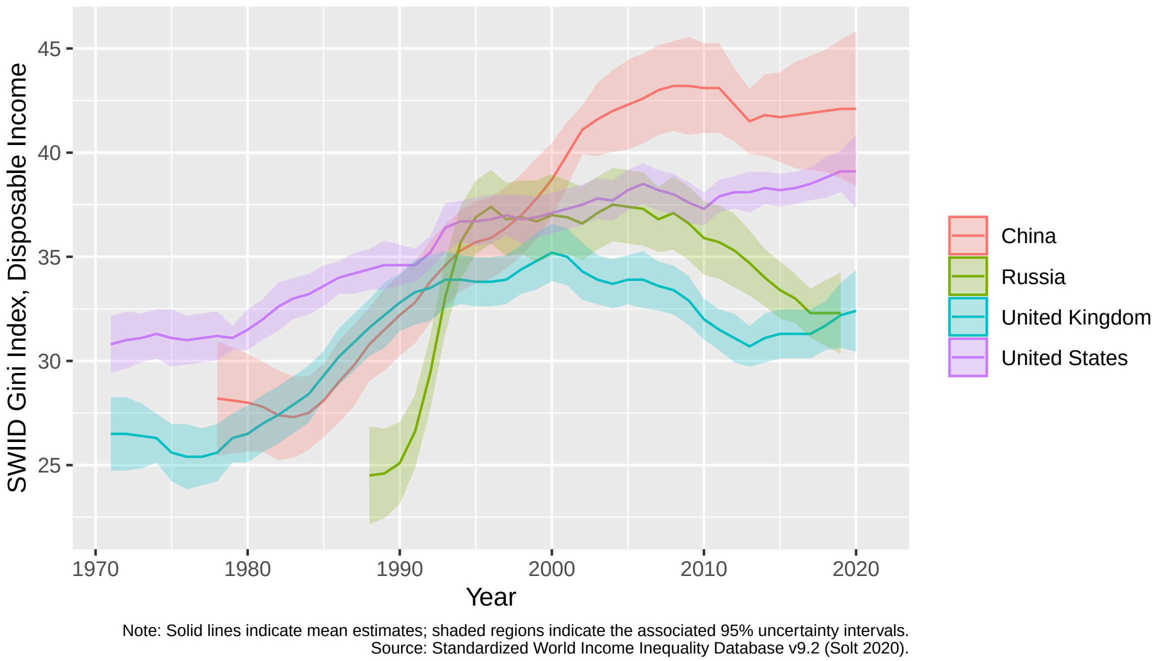


Figure 1: The income gap growth in China, Russia, UK, and USA since 1971

either having cardinal or ordinal utilities [Abdulkadiroglu and Sönmez 2013; Nisan et al. 2007]. The allocation proposed in this text is an offline one-sided resource allocation with cardinal utilities. We direct the reader to: Abdulkadiroglu and Sönmez [2013] for a comprehensive look at matching markets theory, Nisan et al. [2007] for algorithmic game theory, and Vulkan et al. [2013] for general market design. Below, we will review select matching mechanism design solutions to social problems.

One of the most significant scholarly contributions to two-sided matching markets is the *College Admissions and The Stability of Marriage* paper that introduced stable matching and blocking pairs [Gale and Shapley 1962]. The matching algorithm, *deferred acceptance algorithm*, proposed by Gale and Shapley [1962] was shown to be Pareto optimal and strategy proof for two-sided matching. Roth [1984] later showed that the algorithm was in fact equivalent to that used for US hospital-resident matching in the 1950s. This algorithm has provided solutions for many social matching problems including kidney donations, public school-student admissions [Abdulkadiroğlu et al. 2005a,b], and National Hospital-Residency matching [Roth 1984].

The concept of a core allocation with in a one-sided allocation was introduced by Shapley and Scarf [1974], then Roth and Postlewaite [1977] proved that the core allocation generated by the *Top Trading Cycle* algorithm is in fact a unique competitive matching. The core allocation is also Pareto optimal, strategy proof, and individually rational [Ma 1994]. Naturally, core allocations have been adopted for housing allocations in schools, one-sided organ allocation, and time slot allocation on shared resources [Bhalgat et al. 2011].

To the best of our knowledge, using core allocations for the redistribution of surplus or reduction of waste from producers to donation recipients versus independent local donations has not been studied in the algorithmic mechanism design field. However, there exists a number of innovative internet-tech applications that provide platforms for surplus redistribution. We direct the reader to [Cather 2019; WRAP 2021b] for a survey of these digital applications.

1.2 Summary of Contribution

Below are our contributions.

- We examine the creation of waste from overproduction of surplus that is of zero/nearly zero value to producers at the end of a production/market cycle.
- We examine the restriction of access to a resource for the low income classes (zero/nearly zero consumers) through lack of purchasing power at market price.
- We contrast the two options for redistribution, (1) local independent donations between producers and donation centers, and (2) redistribution by way of a global redistributor (what we will call a core redistributor) who collects donations from all available producers and redistributes the surplus to all donation centers respective of their demanded quantities. We show that option 2 or the core allocation maximizes social welfare, and minimizes waste and cost to the producer.
- We also qualitatively study two cases; (1) food waste and food insecurity in the UK, and (2) Los Angeles County's project RoomKey: a pandemic effort to house covid-vulnerable unhoused persons in vacant hotels and motels. Both case studies

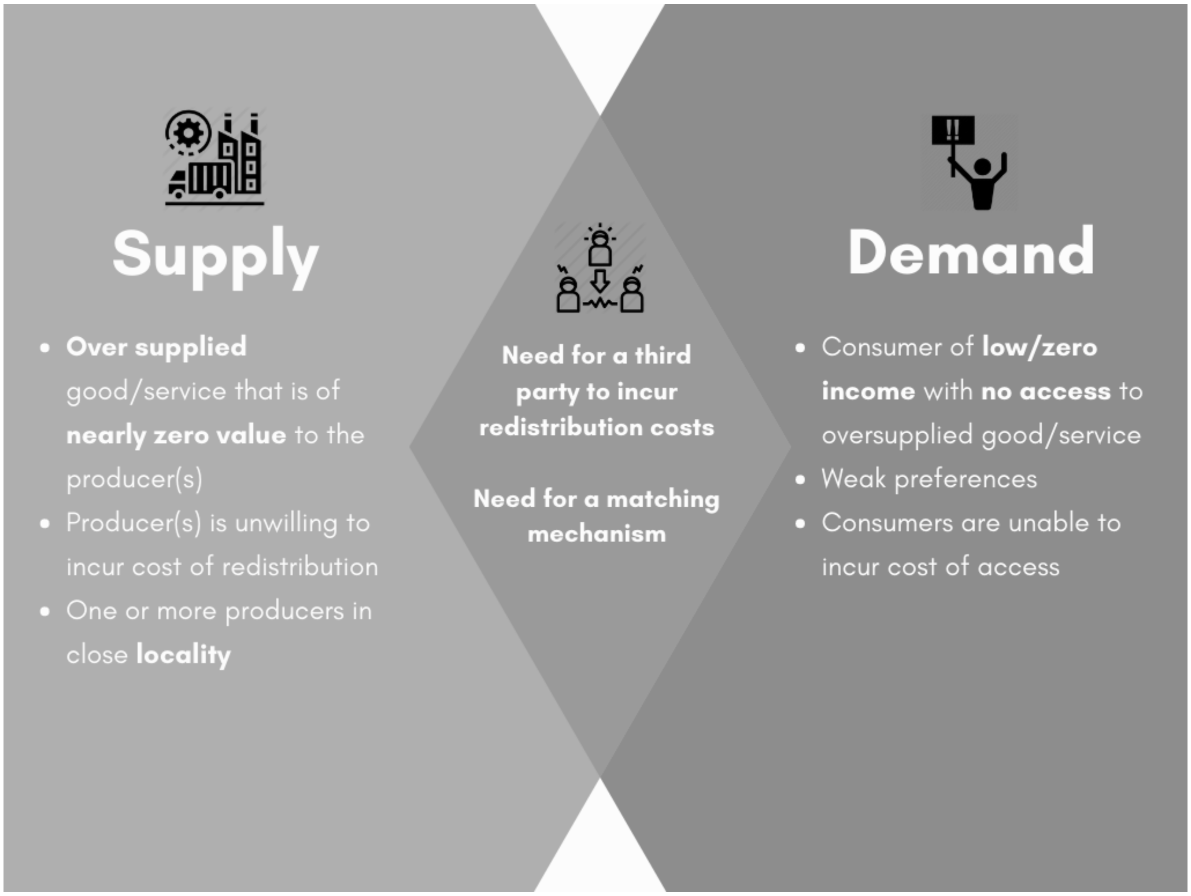


Figure 2: The Waste Creation structure

support the idea of a core redistributor over local independent donation efforts.

2 MODEL

2.1 Waste Creation

2.1.1 Overproduction. We begin at the resource producer or supplier (this could be a manufacturer or retailer), and for simplicity we will assume that the resource is a tangible commodity produced for profit, for example baked goods. Due to a mismatch in demand and supply, this resource is over-produced [Garrone et al. 2014a; Priefer et al. 2016; Thapa Karki et al. 2021]. This is not uncommon, for example, it is common for restaurants, grocery stores, or bakeries of averagely or above-averagely wealthy communities to have excess amounts of over-produced food (probably due to overestimating demand or cost-based planning) that is normally discarded at the end of the day. We will assume that the over-produced resource is either donated or thrown out to the waste bins. At this point, the resource is of nearly zero value to the producer, therefore we will define waste as produce that is of zero/nearly zero value to the producer.

Condition 1. At the end of a production/supply cycle, resources not demanded for consumption are of zero/nearly zero value (waste) to the producer/supplier.

Consider a utility-maximising producer whose utility (ψ) is represented as follows,

$$\psi = TR(Q_d) - TC(Q_p)$$

Where $TR(Q_d)$ is the total revenue from selling quantity demanded, Q_d, and $TC(Q_p)$ is the total cost of producing quantity, Q_p. We assume that at the end of a production cycle, if $Q_d < Q_p$, then we have an excess quantity(Q_e) produced that is not demanded at the market price of the resource. Since the total revenue for Q_e is zero, i.e,

$$TR(Q_e) = 0$$

The utility from Q_e is then

$$\psi(Q_e) = 0 - TC(Q_e)$$

We see here that the quantity of the resource not demanded at the end of a production cycle yields no utility for the producer, and therefore is of zero/nearly zero value to the producer. A good example of this is bakeries because of their short production cycle but we would argue that fast fashion has created a similar condition for some clothing producers but with a longer production cycle.

Because the resource is of nearly zero value to the producer, who is motivated by utility or profit maximization, the producer is unwilling to incur excess or any cost at all in redistributing or discarding the over-produced good.

Condition 2. A producer is unwilling to incur any cost on an over-produced resource of nearly zero value.

From condition 1 above, it's trivial to see that the utility has a negative relationship to the cost spent on excess, and also know that the producers act to maximize utility. The implication then is that the producer is unwilling to incur further cost because that will increase $TC(Q_e)$, which reduces their utility margin. The case study in section 3.1 presents evidence that many producers do in fact act this way.

From conditions 1 and 2 above, we can see that the producers will seek to minimize cost when dealing with the over-produced resources. Two ways that this can be done are to either dispose of the resource as waste or donate to the nearest most convenient donation spot (which could be a resource bank, soup kitchen, welfare retailer, and so on).

Condition 3. Over-produced resources will either be thrown out as waste or get donated to the nearest cheapest donation spot.

Let us assume that the producer can only dispose of the excess quantity or donate it to one donation spot in the collection M. If we adjust $\psi(Q_e)$ to include the cost of disposing(DC) or redistributing(RC) the excess resource, then

$$\psi = -[TC(Q_e) + \min(DC(Q_e), \min_{\forall i \in M} RC_i(Q_e))],$$

where RC_i is the cost of redistributing to a donation spot i. We see that whichever one of the two options costs the least will maximize utility for the producer. This means that either disposal, which is normally not an extra cost, or donation to the nearest donation spot will be the options that maximise profit (utility). Later in the case studies, we will show that many producers lack awareness of the options available to them when dealing with surplus, and more often than not simply dispose of the surplus.

2.1.2 Lack of Access. We will assume the existence of a zero to low income population that demands the over-produced resource but does not have the income to purchase it, therefore lacking access to the resource. This is not uncommon given the well documented marginalized populations that lack access to basic resources like food, housing, clothing, among others (we will term these zero/low income consumers).

The zero/low income consumers normally look to donation spots (or sadly waste disposal spots) for access to the over-produced resource.

Condition 4. Low income consumers are unable to access over-produced resource at market price.

From the law of demand and the linear demand curve, we know the quantity of resource demanded in a perfect market is defined by,

$$Q_p = a - bP$$

Where a and b are constants for factors other than the price of the resource, and P is market price. Considering the consumer is of low income, let us assume the income (I_l) is defined as,

$$I_l \leq \frac{a}{b} \leq P.$$

It is easy to see that even at the upper bound of $I_l = \frac{a}{b} = P$, the quantity demanded is,

$$Q_p = 0, \text{ if } I_l \leq \frac{a}{b} \leq P \text{ is true.}$$

If access to a priced resource is equivalent to ability to afford/purchase the resource (purchasing power), then we see that indeed low income consumers have no access to the over-produced resource at market price.

Condition 5. Resources accessed as donations or waste are demanded at zero/nearly zero prices

From condition 3 and 4, we know that producers will either donate or dispose of the excess resource, and low income consumers that demand the resource can not access it at market price. Therefore, for the disposed resource, it is trivial to see that low income consumers that turn to waste disposals do not intend/expect to pay any price for access to the waste.

And for donation centers, for low income consumers to demand a quantity, $Q_l > 0$, the price (P_e) of the excess resource has to be marked down to,

$$0 \leq P_e < \frac{a}{b}$$

Condition 6. Low income consumers have weak preferences over the over-produced resource due to lack of access to resource at market price

This structure of overproduction of resources that become nearly zero value (surplus) resources, and lack of access to the resource due to zero/low income demand is evident in many industries, most notably, the food industry, and in special cases the housing (emergencies), and clothing (fast fashion) industries as well. The next subsection will set up and propose an algorithmic solution for the redistribution of the over-produced resource. While the above conditions seem trivial, they will be crucial in proving why a core redistribution is the most optimal solution for the problem of overproduction and waste reduction.

2.2 Algorithmic Waste Redistribution

From the waste creation structure, the producers with the over-produced resource to donate will now become donors in the redistribution model. We are aware of the alternative sources of donations, like private donations from households, but choose to ignore them here for simplicity, as we assume that these individual household contributions are insignificant in comparison to large scale producers. Because the consumers are represented as donation spots in the redistribution model, any zero/low income consumers that look outside of donation spots for resource access are ignored in this model as well. Donation spots could be food banks, goodwill stores, soup kitchens, homeless shelters, and any other centers through which the marginalized receive basic resources in quantities larger than a household. We now set up the redistribution problem.

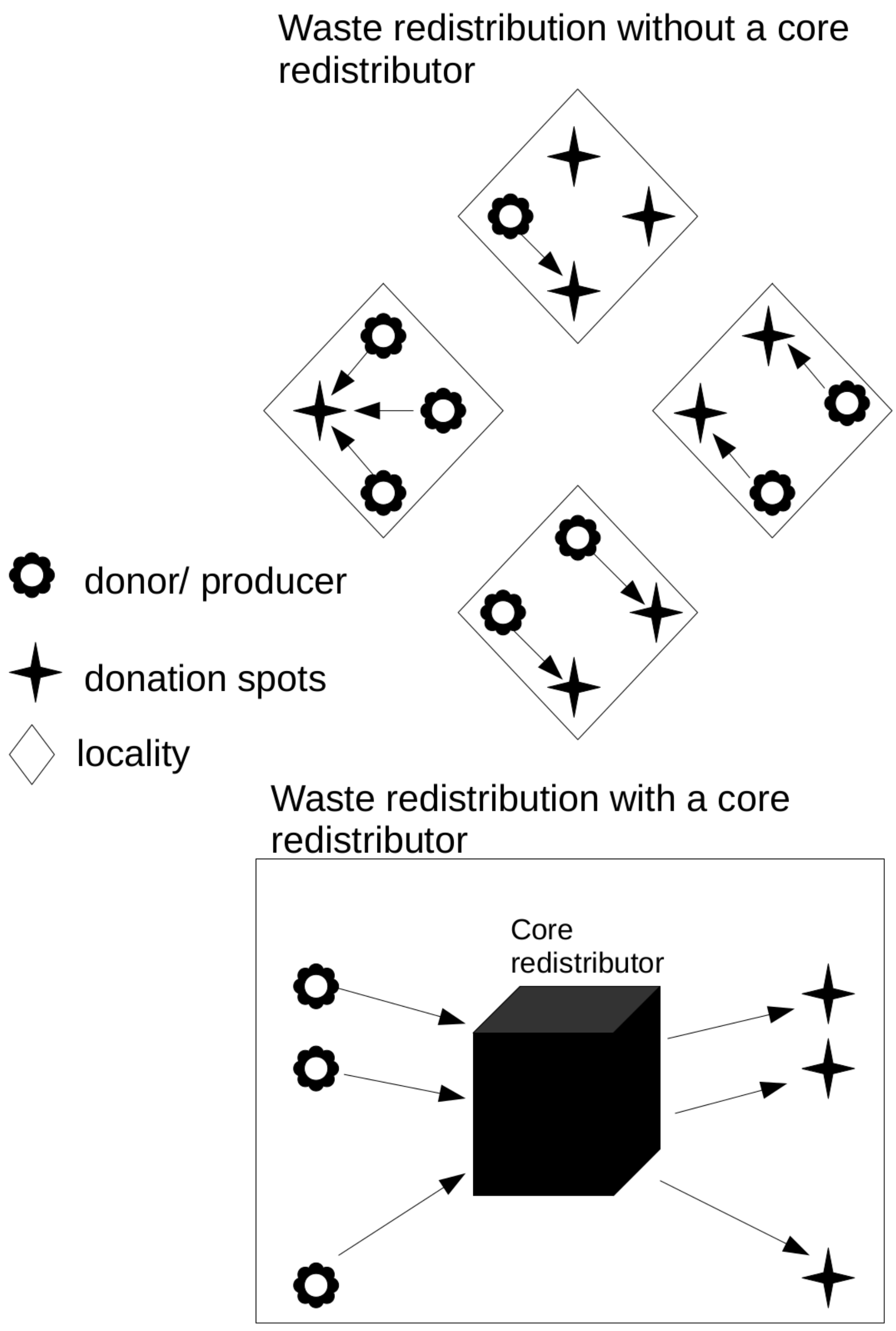


Figure 3: The waste redistribution solutions with and without a core redistributor

2.3 Formal Model

Consider M donors looking to donate an over-produced resource, where each donor can donate at most 1 unit of the resource. Each donor also wishes to minimize the cost of redistribution for this over-produced resource which we represent as a utility function on the cost of redistribution

$$\psi_d = \frac{1}{RC(Q_e)},$$

where

$$RC(Q_e) = \begin{cases} 1 & \text{within locality} \\ 2 & \text{outside of locality} \end{cases}$$

Also consider N donation spots that demand varying quantities of the over-produced resource with each quantity demanded, Q_d units (Each donation spot can have/demand at most Q_d units of the resource). Each donation spot wishes to have enough stock to satisfy the demand from their consumers. Therefore, we will assume that the total demanded units from all consumers at each donation spot is at most Q_d units. Each donation spot has some welfare utility,

$$\psi_w = Q_d - \max(Q_w, Q_{nn}),$$

where the cost Q_w is the quantity wasted at the donation spot and Q_{nn} is the quantity not met in the case that donated quantity is less than Q_d. We will assume that the M donors and N donation spots are arbitrarily distributed among k many localities. Therefore, each locality (which is a physical geography where the producers (donors) and consumers (donation spots) are located) has some fraction of M and N.

Since the overall goal is to minimize waste ($\sum_N Q_w$), we also have a waste utility function,

$$\psi_r = \frac{1}{\sum_N Q_w}$$

A good solution should maximize waste utility, welfare utility, and the donors' utilities. Below we will consider two solutions, one with a core redistributor or central clearing house (like a government or a donation network), and one without a central clearing house or core redistributor (see figure 3).

2.3.1 *Without a Core Redistributor [WOC].*

Theorem 1. If donors/producers look to minimize cost of redistribution, without a third party to carry that cost, the amount of waste grows monotonically with the number of producers, and welfare utility is not maximized

Proof. We have M donors each donating 1 unit and N donation spots each demanding Q_d units, arbitrarily distributed among k localities. From the definition of $RC(Q_e$ and conditions 2 and 3 in section 1.1.1, the donor will always donate within their locality to minimize cost. Since the cost within a locality is the same, each donor i will donate to some donation spot j in the same locality with equal probability,

$$P_{i,j} = \frac{1}{\text{no. of donors in a locality}} \tag{1}$$

We can derive the expected utility for each donor, E_i to be,

$$E_i[\psi_d] = -[TC(Q_e) + \min(DC(Q_e), \min_{\forall i \in M} RC_i(Q_e))]$$

$$E_i[\psi_d] = -[TC(Q_e) + 1],$$

where $\min(DC(Q_e), \min_{\forall i \in M} RC_i(Q_e)) = 1$ from choosing to donate to the nearest. Since M and N are arbitrarily distributed among k localities, we will define the number of donors in any one locality as m, where $m \leq M$ and $\sum_k m = M$, and the number of donation spots in that same locality as n, where $n \leq N$ and $\sum_k n = N$.

The probability, $P(X = x)$ that a donation spot, j, gets donations from x many donors in a locality is;

$$P(X = x) = \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} \tag{2}$$

We can now derive the expected utility for each donation spot, j, within a locality to be,

$$E_j[\psi_w] = \sum_{x=0}^{m} \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} (Q_d - \max(Q_w, Q_{nn})) \tag{3}$$

We can also express $\max(Q_w, Q_{nn})$ as

$$\max(Q_w, Q_{nn}) = |x - Q_d|.$$

From that $E_j[\psi]$ can be rewritten as,

$$E_j[\psi_w] = \textstyle\sum_{x=0}^{m} x \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} - \sum_{x=Q_d+1}^{m} (x - 2Q_d) \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} \tag{4}$$

Notice that,

$$E_j[\psi_w] = \underbrace{\sum_{x=0}^{Q_d} x \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x}}_{\text{expected satisfication}} - \overbrace{\sum_{x=Q_d+1}^{m} (x - 2Q_d) \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x}}^{\text{expected waste cost}} \tag{5}$$

We can now also derive the expected waste for each j,

$$E_j[Q_w] = \sum_{x=0}^{m} (x - Q_d) \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} \tag{6}$$

And expected total waste reduction utility,

$$E[\psi_r] = \frac{1}{\sum_{j \in N} E_j[Q_w]} \tag{7}$$

Notice that as long as the number of donations $x > Q_d$ for any j, neither total waste reduction utility nor welfare utility are maximized because there will be waste and cost proportional to the difference between x and Q_d. □

Lemma 1. The probability, $P(x > Q_d) > 0$ if $m >> n$

Proof. From equation (5),

$$P(X = x) = \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x} \tag{8}$$

The probability that $x > Q_d$ for a certain j becomes,

$$P(x > Q_d) = \sum_{x=Q_d+1}^{m} \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x}$$

Which is equivalent to,

$$P(x > Q_d) = 1 - \sum_{x=0}^{Q_d} \binom{m}{x} \left(\tfrac{1}{n}\right)^x \left(1 - \tfrac{1}{n}\right)^{m-x}$$

From Heoffding's inequality for the upper bound of the binomial cumulative distribution function [Hoeffding 1994],

$$P(x > Q_d) > 1 - \exp\left(-2m(\frac{1}{n} - Q_d\frac{1}{m})^2\right)$$

Consequentially,

$$1 - \exp\left(-2m(\frac{1}{n} - Q_d\frac{1}{m})^2\right) > 0 \tag{9}$$

For 9 to hold,

$$1 > \exp\left(-2m(\frac{1}{n} - Q_d\frac{1}{m})^2\right)$$

$$\ln 1 > \ln\left(\exp\left(-2m(\frac{1}{n} - Q_d\frac{1}{m})^2\right)\right)$$

$$0 > -2m(\frac{1}{n} - Q_d\frac{1}{m})^2$$

$$0 < (\frac{1}{n} - Q_d\frac{1}{m})$$

$$\frac{1}{n} > Q_d\frac{1}{m}$$

$$m > Q_d n$$

Observe then that $P(x > Q_d) > 0$ if $m > Q_d n$. And this is exactly the condition that arises in affluent neighborhoods, where the number of donors/donations is normally much larger than the number of donation spots and their demand ($m >> n$). This creates a scenario where multiple donors in an affluent locality donate to the few donation spots closest to them and therefore create more waste at those donation spots as they are overwhelmed with supply. In this situation, $E_j[Q_w]$ will grow monotonically for the donation spots in localities where $m >> n$. Which directly implies that the expected unsatisfied quantity, $E_j[Q_{nn}]$, for the donation spots in less affluent neighborhoods will grow monotonically as well because m is a fraction of M. □

2.3.2 With a Core Redistributor [WC].

Theorem 2. With a core redistributor/central clearing house to cover the cost of redistribution and ensure a core allocation [Shapley and Scarf 1974], virtually all surplus is redistributed (waste minimized), welfare utility, and donor utility are also maximized

This proof will take two cases, (1) one where the total quantity donated, $\sum_i Q_e$, is greater or equal to the total quantity demanded, $\sum_j Q_d$, and (2) another where $\sum_i Q_e < \sum_i Q_d$. The proofs follow.

Proof. When $\sum_i Q_e \geq \sum_j Q_d$, the core allocation is obtained from a simple algorithm 1 stated below:

Algorithm 1: Surplus redistribution when $\sum_i Q_e \geq \sum_j Q_d$

(1) Collect the quantity donated, Q_e from all donors
(2) Arbitrarily order all donations spots in a queue
(3) Iterate through queue, and allocate each donation spot its quantity demanded, Q_d
(4) Terminate when queue is empty

Observe that because $Q_e \geq Q_d$, each donation spot should get exactly the quantity demanded, Q_d. Therefore, for each spot, j,

$$\psi_j = Q_d - \max(Q_w, Q_{nn})$$

And we know,

$$\max(Q_w, Q_{nn}) = |x - Q_d| \text{ and } x = Q_d$$
$$\psi_j = Q_d - 0$$
$$\psi_j = Q_d$$

Observe that this is the maximum possible utility a donation spot can achieve. That leads us to the maximum total welfare utility from the sum of all donation spots, $\sum_{j \in M} Q_{d,j}$

It also follows that the waste for each donation spot, $Q_{w,j} = 0$, and since the cost of redistribution is taken on by the core redistributor, the cost $RC(Q_e)$ for each donor is also 0. In the case where $\sum_i Q_e > \sum_i Q_d$, we will have some surplus $Q_w \equiv Q_e - Q_d$, one could imagine this surplus going to another network of donation spots.

When $\sum_i Q_e \leq \sum_j Q_d$, how a core allocation is found is non-trivial. We will set up the problem as a linear program subject to constraints that ensure a fair allocation with maximum welfare utility and minimum waste. Let $\alpha_{i,j}$ be a variable to ensure that each donation spot and donor are fully satisfied, that is, that each donor's donation is taken and each donation spot gets some quantity that maximises its possible utility. And let $u_{i,j}$ be the utility donation spot j would get from taking donor i's donation. The LP follows:

$$\text{Maximize} \sum_{i,j}(a_{i,j}u_{i,j})$$

$$\text{subject to; } \sum_i(a_{i,j}) \leq 1, \text{for each } j$$
$$\sum_j(a_{i,j}) = 1, \text{for each } i$$
$$0 \leq a_{i,j} \leq 1, \text{for each donation } (i,j)$$

This LP will produce multiple allocations in most cases. We will choose the allocation with minimum waste. □

Lemma 2. When $\sum_i Q_e \leq \sum_j Q_d$, a zero waste core allocation always exists.

Proof. The simple proof is that one can always allocate each donation spot quantity, $Q = (\frac{\sum_i Q_e}{\sum_j Q_d})Q_d$. This is both a fair allocation in terms of equality of the distribution but also ensures no one donation spot j gets $Q > Q_d$, therefore there is no waste created. □

2.3.3 Social Welfare and Pareto Efficiency.

Let's define a total social welfare that depends on the utilitarian assumptions that a society looks to provide resource access to every individual and also minimize resource waste. The total social welfare utility becomes,

$$\psi_{social} = \sum_j(\psi_j - Q_{w,j})$$

From theorem 1 and 2, because a core redistribution would maximise every donation spot's utility while minimizing the amount of waste created in the redistribution, we can conclude that we do in fact achieve a Pareto Improvement on the social welfare with a core allocation. This means that a core allocation would help give low income consumers access to the surplus resource without creating any further waste for the society.

2.3.4 Multiple resources (bundle). If we relax the one resource assumption to allow for multiple resources, one could imagine breaking the bundle of resources into independent resource allocations, where the total utility for all resources is an additive sum of all the independent utilities from each resource. It is trivial to see that the maximization of the independent utilities is a maximization of the total utility.

2.3.5 Cost of Redistribution and Individual Rationality. We make a big assumption that the core redistributor would take on the cost of redistribution, as we imagine some welfare budget is normally available to donation centers through the federal, state, or local governments. The lack of such funding would present a major complication for this model, but we reckon that it would be easier for a network of donation centers to carry the cost of redistribution than individual centers. Future work could explore the implications of the cost of redistribution, for example, why should a donation center in an arbitrary or affluent neighborhood choose to share this cost with other donation centers in a core if federal, state or local government funding is not available?

3 CASE STUDIES

3.1 Food surplus redistribution in the UK

The first of our case studies will look at the concurrent paradoxical existence of food waste and food insecurity in developed countries [Galli et al. 2019; Thapa Karki et al. 2021]. The case study will summarize the current state of food waste and food insecurity in the UK (The UK's food waste and redistribution efforts are some of the most studied in the world, making it an easy choice for a case study for this paper). The summary is mainly drawn from data and other resources provided by the Waste and Resources ACT Programme (WRAP). The case study will also examine one of UK's largest food redistributor, FareShare, a non-profit that redistributes food from suppliers to local recipients like food banks and soup kitchens so as to eliminate food waste. This examination of FareShare is done through reviewing FareShare reports and a number of other studies published on FareShare operations in parts of the UK. The case study will conclude with discussion to support the adoption of larger redistribution networks with core allocations.

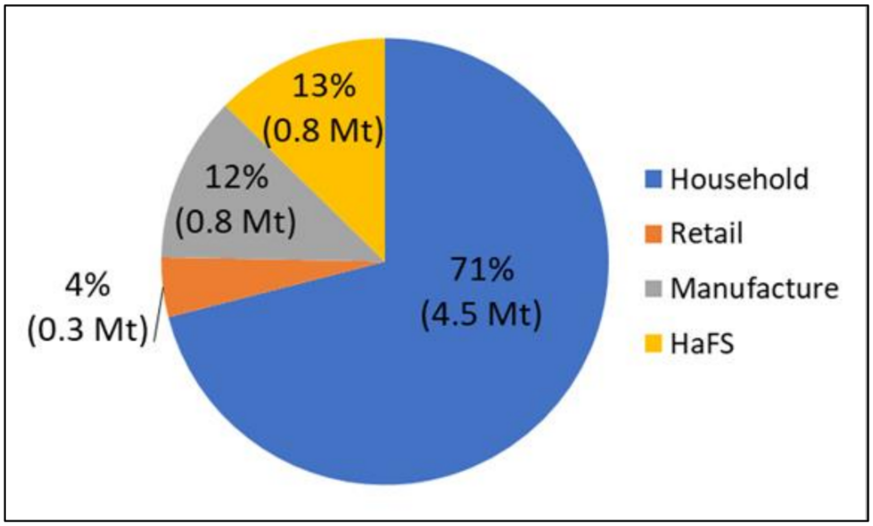
3.1.1 State of food waste and Food insecurity in the UK. According to WRAP, roughly 3.6 million tonnes of food is wasted annually by the food and hospitality industry in the UK [Filimonau et al. 2019; WRAP 2021a]. Further break down shows that over 2 million tonnes of the waste is edible before it becomes waste, what most literature calls *fit for purpose* [WRAP 2021a]. FareShare reckons about 1.3 billion meals could be produced from this 2 million tonnes [Fareshare 2021a]. As shown in figure 4, most of this waste is created by households and therefore makes the problem of food waste redistribution that much harder because coordination of collection and redistribution would be much more costly at the household level. Figure 4 shows the fractions of food waste created by each sector in the UK. This paper argues for large scale redistribution, nationwide if possible, at the supply level, that is redistribution of surplus from producers (farmers, manufacturers, restaurants and other retailers) to recipients at donation centers (food banks, soup kitchens, shelters, among others) through a core redistributor (like FareShare or Feeding America).

On a positive note, the same 2021 WRAP report shows that the amount of food waste produced in the UK is in fact reducing and is projected to reduce by over 50% by 2030 if the currently proposed steps for food waste redistribution in the UK are met (see Figure 5) [WRAP 2021a]. However, to meet the goals proposed for waste reduction requires a coordinated effort between academics, policymakers, and involved actors on the ground. This paper aims to contribute solution ideas to such efforts in and beyond the UK, to other countries where food surplus redistribution is not as well established.

This paper's focus is on the 29% or 2 million tonnes created by the food industry that could be redistributed as edible food because evidence shows that food disposal is still the default option for suppliers and retailers [Ciulli et al. 2020; Filimonau and Gherbin 2017; Garrone et al. 2014b; Mena et al. 2011].

FareShare is a UK based non-profit that looks to redistribute edible food, that could be wasted by food producers, to different donation recipients that serve persons facing food insecurity [Alexander and Smaje 2008; Fareshare 2021a]. As mentioned earlier, 1.3 billion meals could be created from the proportion of food wasted by the food industry [Fareshare 2021a]. According to current estimates from FareShare and Food and Agricultural Organization of the United Nations (FAO), 8.2 million people in the UK struggle to find food [Loopstra et al. 2015; Thapa Karki et al. 2021]. That means the 1.3 billions meals wasted could provide a meal for each one of these 8.2 millions for 159 days of a calendar year. This is exactly FareShare's goal.

FareShare either receives donations from donors who deliver or collects donations from those who can not deliver, then packages and redistributes these donations to local donation spots like shelters, food banks, soup kitchens among others [Alexander and Smaje 2008]. **Note: Each FareShare independently serves a particular locality.** Within a locality, a FareShare location serves as the core redistributor between local producers and local charities. The case study in [Alexander and Smaje 2008] showed that barely any waste is created within the local FareShare surplus-donation redistribution. This is clearly shown in Figure 6, the FareShare donation chain in Southampton, UK. Observe that only 8% of the waste created by the suppliers in this Southampton study ended up becoming waste [Alexander and Smaje 2008]. Evidence from the Southampton study supports the idea of a core redistribution, but of course this data is only local to Southampton. National figures show that FareShare is only salvaging a small fraction of the food surplus wasted and reaching a small fraction of persons facing food insecurity. This could be a result of the fragmentation between FareShare locations, where a collective network effort could cover wider areas and offer core allocation advantages on a wide scale. Figure 7 shows the locations of FareShare sites[left] and the distribution of income in the



** Food waste at wholesale and in litter is excluded from this analysis as the percentage of inedible parts is unknown and difficult to predict. Data for household also includes waste to sewer, which is not currently available for other sectors.*

Figure 4: Amount of edible food waste created by sector in the UK. Source: WRAP [2021a]

UK[right]. A far out view of these images together seems to imply that FareShare locations are in places of above average income in the UK. But this alone is not enough to explain why FareShare may only be reaching 1.2 million of the 8.2 million people that struggle to find food in the UK. Figure 8 shows that there exists quite a number of localities with higher cases of food insecurity and low income that are not covered by FareShare.

3.1.2 Analysis of FareShare's model and UK Food Waste. From the Southampton and London studies of FareShare operations [Alexander and Smaje 2008], we have evidence that adopting a unified effort to redistribute food surplus has many advantages, best of which is the minimization of food waste. The studies, however, do not give us clear insight into the cost and welfare optimization within Southampton and London. Despite the local success with waste minimization, National efforts are still only achieving minimal surplus redistribution and welfare maximization (Evident from the 8 million that still struggle to find food in the UK). One of the biggest challenges for food waste redistribution is the difference in goals of the actors involved. This is perhaps why "FareShare still only has capacity to handle about 5% of supermarket surplus—equivalent to some 36 million meals—to avoid it becoming food waste (FareShare, 2018). There remains a good deal of work to be done to effectively handle the remaining 95%" [Porter 2020]. Ciulli et al. [2020]; Diaz-Ruiz et al. [2019]; Facchini et al. [2018a,b]; Thapa Karki et al. [2021] further prove that the failures of food redistribution at micro-levels (localities) are mainly due to independence between efforts keeping them local and fragmented. Perhaps a more macro-level approach to food waste redistribution (core redistribution) like one proposed by this paper could be the best path to that 2030 50% food waste reduction goal.

Of course, there are more limitations to the redistribution of food surplus beyond algorithmic or engineering problems. The FareShare study showed that some suppliers are unaware of donation as an option for surplus redistribution [Alexander and Smaje 2008; Filimonau and Gherbin 2017]. While among those that are aware, most feel pressure to resell waste at discounted prices due to the revenue maximisation requirements of their corporate owners, to whom redistribution of food surplus is not viable [Alexander and Smaje 2008; Ciulli et al. 2020; Filimonau and Gherbin 2017; Filimonau et al. 2020]. Furthermore, many producers cite the fear of liability claims as the biggest reason why they choose not to donate [Alexander and Smaje 2008; Ciulli et al. 2020; Filimonau and Gherbin 2017; Filimonau et al. 2020; Mena et al. 2011; Patel et al. 2021]. This, however, is one factor that could be solved with a core redistributor who can standardize and regulate the quality of donations sent to recipients so that donors are spared the cost of standardization and the liability from failure to do so. FareShare stands as evidence of this [Alexander and Smaje 2008]. Difficulties in predicting supply and demand can also be best dealt with by a core redistributor. This is shown in Davis et al. [2016] who propose the use of time series models to predict food donation behavior at 6 different brokerage food banks in the US to within 10% accuracy loss. Davis et al. [2016] also show that it is easier to generate food donation forecasts with higher accuracy at a network level than at the decentralized level. Further empirical evidence for the need of third party redistributor is given by, Phillips et al. [2013], who show that the costs for redistributing the surplus can be offset by

	2007*		2018			
	Tonnes	Per capita (kg)	Tonnes	% change	Per capita (kg)	% change
UK total post-farm food waste	11,200,000	181	9,500,000	15%	143	21%
UK post-farm gate food waste (excluding inedible parts)	8,200,000	132	6,400,000	21%	96	27%

** In Historical changes and how amounts might be influenced in the future WRAP 2014, WRAP made the case for a baseline year of 2007 against which to assess changes in UK food waste over time. This was on the basis that a) there is robust data on the largest fraction of UK food waste from that year (i.e. household food waste; ca 70% of the total post-farm gate) and b) this is when the UK began large-scale interventions to reduce food waste (which were aimed exclusively at household food waste until 2010 – with a focus on supply chain food waste commencing under Courtauld 2 in 2010, and in 2012 on food waste from the hospitality and food service sector[18].*

	2007		2018		2030		Reduction in tonnage required to achieve SDG12.3 (2018 to 2030)			% Reduction per capita		
	Total food waste (t)	Total food waste per capita	Total food waste (t)	Total food waste per capita	Total food waste (t)	Total food waste per capita	Wasted food (t)	Inedible parts (t)	Total food waste (t)	2007-2018	2007-2030	2018-2030
Household	8,100,000	132	6,600,000	100	4,400,000	63	1,827,000	373,000	2,200,000	24.2%	52.3%	37.0%
Retail	290,000	5	277,000	4	188,000	3	89,000	n/a	89,000	10.6%	42.0%	35.7%
Manufacture	1,900,000	30	1,500,000	23	1,050,000	15	230,000	220,000	450,000	24.6%	49.9%	33.9%
HaFS	920,000	15	1,100,000	17	685,000	10	363,000	52,000	415,000	-13.7%	32.6%	40.6%
Total	**11,210,000**	**181**	**9,477,000**	**143**	**6,323,000**	**91**	**2,509,000**	**645,000**	**3,154,000**	**20.9%**	**50.1%**	**36.9%**

Figure 5: Projections of food waste and surplus in 2030 in comparison to 2007 and 2018. Source: WRAP [2021a]

Southampton FareShare: 'food flow' summary

Food	(kg)	% total by weight	% re-entering waste stream	% other disposal
Offered	2178	100	0	0
Accepted	2056	94	6	0
Diverted to animal sanctuary	51		0	2
Discarded at FareShare	44		2	0
Given to projects	1961	90	0	0
Preparation-stage waste	392		18	0
Served to clients	1475	68	0	0
Discarded by clients	220		10	0
Other food discarded	94		4	0

Figure 6: Food Donation Flow in Southampton with FareShare as the core redistributor. Source: Alexander and Smaje [2008]

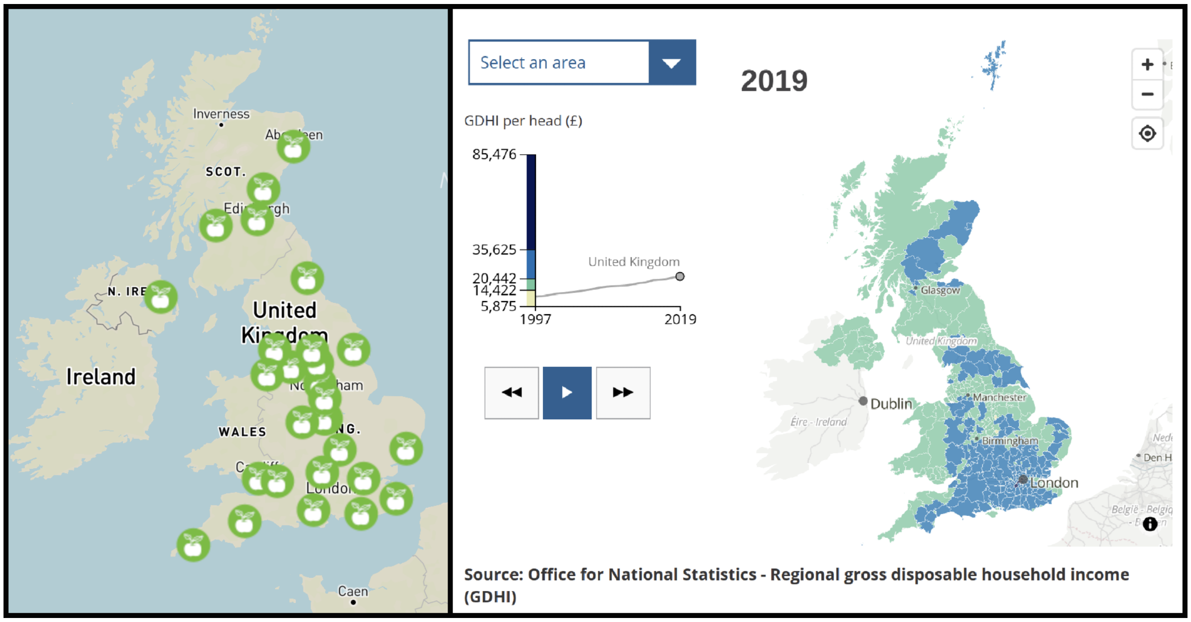


Figure 7: LEFT:Map showing FareShare locations in the UK [Fareshare 2022]. RIGHT: Map showing Income distribution in the UK. Source: of National Statistics [2019]

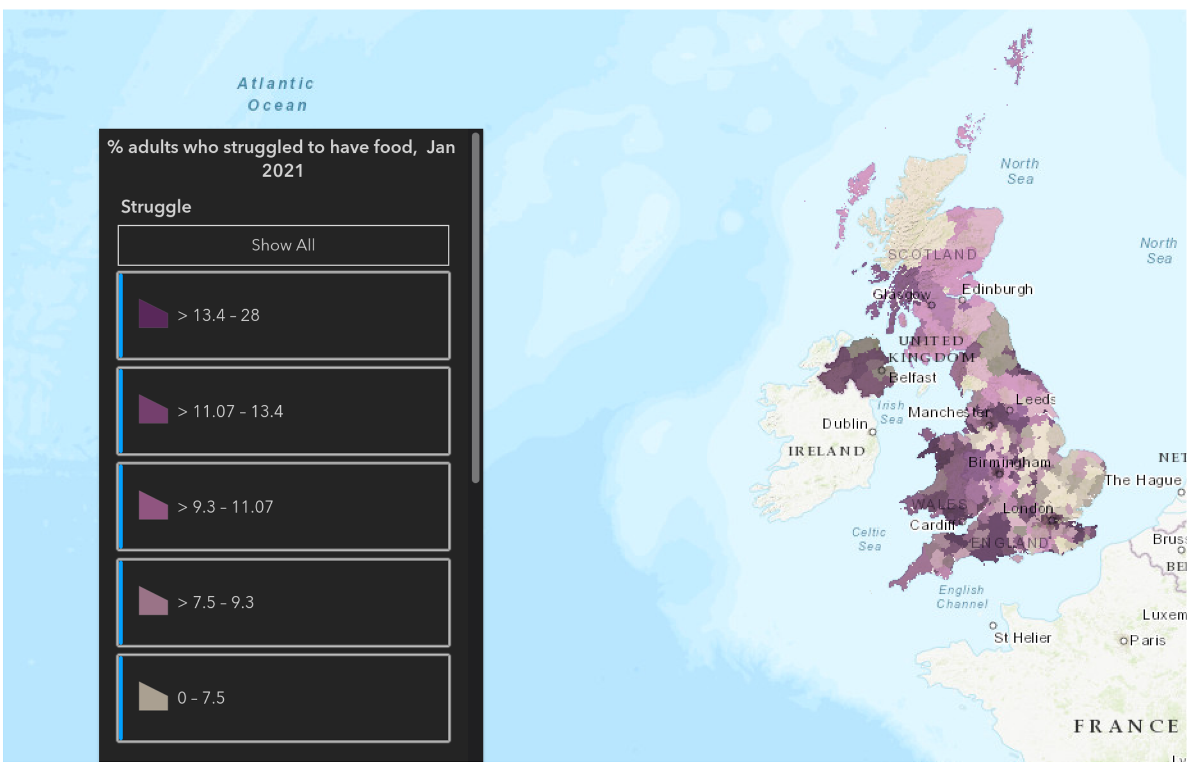


Figure 8: Map showing food insecurity in the UK. Source: Fareshare [2021b]

large recruitment of suppliers and recipients under on core redistributor. This can be done by expanding the core redistributor's locality. We advise the reader to look at [Phillips et al. 2013] for a numerical examination of food redistribution with localities, and at Alexander and Smaje [2008]; Ciulli et al. [2020]; Thapa Karki et al. [2021] for further discussion of the limitations of food surplus core redistribution.

3.2 Housing waste redistribution in LA county (Project Roomkey)

Emergency situations provide the most clear-cut evidence of the oversupply-lack of access systematic mismatch highlighted by this text. That is, in cases of natural disasters and other emergency situations, low income communities are normally left without resources in high demand while high income places are left with oversupply of the same resources (Puerto Rico after hurricane Maria and New Orleans after hurricane Katrina are two popular examples) [Fussell 2015; García-López 2018; Garfield 2007; Henrici et al. 2015]. This has been evident in the COVID-19 pandemic as well. Therefore, this case study will explore emergency housing during the COVID-19 pandemic. We will particularly focus on LA county's Project Roomkey, "a collaborative effort by the State, County, and the Los Angeles Homeless Services Authority (LAHSA) to secure hotel and motel rooms for vulnerable people experiencing homelessness. It provides a way for people who don't have a home to stay inside to prevent the spread of COVID-19" [of Los Angeles 2020]. Here we will follow the same structure as the food waste case study, beginning with a look at the state of Project Roomkey and how it relates to this paper's proposed hypothesis on oversupply and lack of access. We will follow that with an analysis of Project Roomkey in relation with theorem 2.

3.2.1 State of Project Roomkey. During the early months of the pandemic (March 2020 - October 2020), most of the US mandated state-wide lockdowns so as to slow down the spread of the coronavirus. These lockdowns had unessential businesses shutdown and everyone besides non-essential workers were asked to stay at home. This meant that **hotels and motels around the country were left with an oversupply of vacant rooms (low value supply)** [Ananya Roy and Eden 2020; Padgett et al. 2022; Roy and Rosenstock 2021]. However, while the majority of the world could shelter in, **the houseless were left vulnerable to the coronavirus (low income demand and lack of access to housing)**. Project Roomkey is the collaboration between the state of California, city of LA, and LAHSA, under which vacant rooms were acquired to house eligible houseless persons. The assignment was done using Algorithm 2 [Authority 2021].

Eligibility and priority for assignment of interim housing under Project Roomkey are determined by "high-risk profile for COVID-19"[Authority 2021]. According to LAHSA, high-risk is defined or determined by age, chronic health condition, COVID-19 asymptomatic condition, persons currently staying in congregate facilities. A priority list is generated from the above criteria [Authority 2021].

Initially, the city projected that they would house over 15,000 of the LA area's 60,000 unhoused persons [Authority 2021]. However, as shown in figure 9, only about 30% of this goal was achieved before it was shutdown in late 2020. LAHSA's leadership cited a lack of personnel and funding as the reason it did not succeed [Smith and Oreskes 2020]. Analysis below will show that there were also some inefficiencies in their room allocation procedure in algorithm 2.

Algorithm 2: The assignment procedure employed by LAHSA under Project Roomkey

Organize agents in some priority list
for *Each eligible agent on the list* **do**
- Assign agent to a local homeless service provider
- The local homeless service provider assigns the agent a housing option according to their needs

3.2.2 Analysis of Project Roomkey. The immediate point of note is that preferences and assignments are restricted by locality from the fact that the housing options are distributed among local homeless service providers who oversee the local hotel and motel room matching [Authority 2021]. While LAHSA is in the position of a core redistributor, their role in the matching only goes as far as acquiring the vacant rooms, but the matching of persons to these rooms is done by on-site service providers.

From figure 9, we see that throughout the entire lifetime of Project Roomkey, the number of rooms contracted was consistently higher than the number of rooms occupied, despite the number of houseless folks being much higher than even the number of projected rooms. It is trivial to prove that with a core redistributor, the number of contracted rooms would be easily equal to the number of occupied rooms. That is, the amount of waste would be minimized. Aguma [2022] shows that a core allocation, for this Project Roomkey assignment problem, would achieve Pareto optimality, that is, a core allocation would maximise individual social welfare given some priority ranking on the persons seeking vacant rooms (note that a priority ranking is already weakly-established by LAHSA's eligibility list). Additionally, LAHSA, the state, and LA county, as the third party redistributor, incurred the cost of redistribution, that is, contracting rooms and covering transportation costs to the vacant rooms [Authority 2021]. We advise the reader to look at [Aguma 2022] for a comprehensive examination of Project Roomkey in contrast to a core redistribution, and [Ananya Roy and Eden 2020; Padgett et al. 2022; Roy and Rosenstock 2021] for the successes and failures, outside matching algorithms, of hotel housing during the pandemic.

4 CONCLUSION

4.1 Discussion

This text examined the paradoxical mismatch where both overproduction of highly demanded resources and a lack of access to the same resources exist within the same communities. We have shown that the surplus created, normally from overestimation of demand and/or cost reduction planning for the resource, is of zero to low value for the producer because it yields zero or negative utility with respect to revenue returns and cost. For a producer looking to maximize profit, the rational option for dealing with this surplus has to be the cheapest one, which, from evidence in the

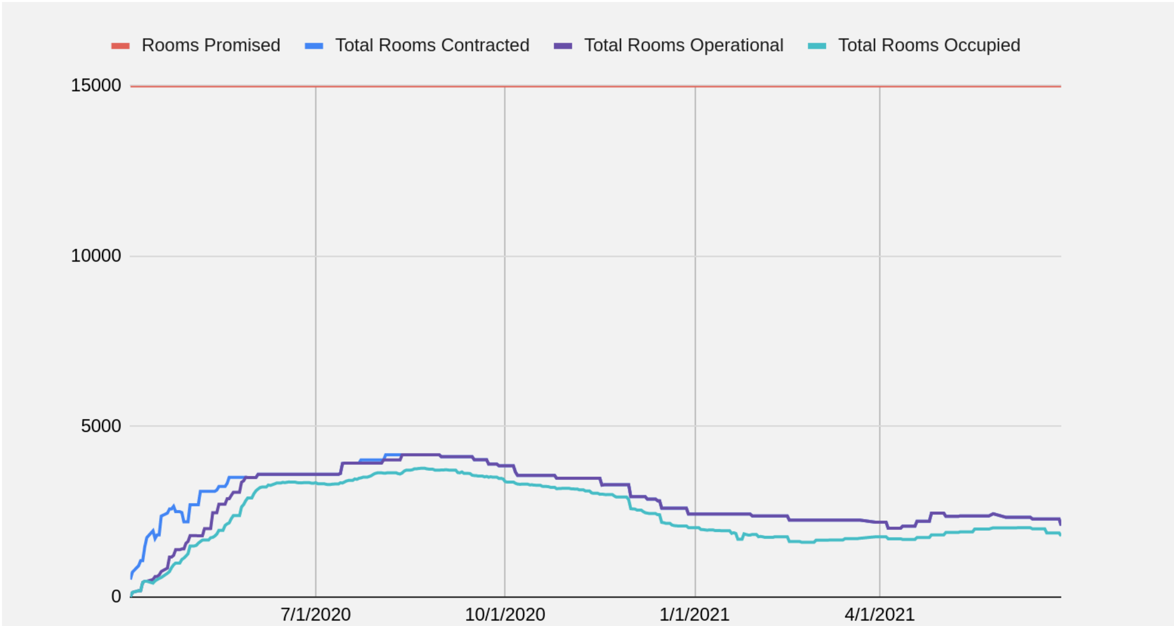


Figure 9: LA County Project Roomkey Tracker [Tracker 2021]

food surplus case study, is normally waste disposal. We also proved that for those in zero to low income classes, there is a lack of access to the oversupplied resource at market price because purchasing power determines access. They therefore turn to donation/welfare centers to access these sometimes essential resources. How this surplus is redistributed to donation centers is crucial to waste and cost minimization, and welfare maximization.

We propose the adoption of a core redistribution wherein a third party like the federal or local government or a network of donation centers collects all the surplus from producers and appropriately redistributes it to donation centers. The core redistributor incurs the cost of redistribution which, again from evidence from FareShare and project Roomkey, is plausible. We showed that this core allocation maximizes welfare for the donation centers, minimizes cost to the producer, and minimizes waste created within the supply chain. This is backed by evidence in the UK food waste redistribution case study in section 3. That is, a study on the operations of FareShare in the city of Southampton showed that the amount of waste created between redistributing surplus from donors to donation recipients is about 8% of the total surplus. This is, however, not the case when we look at the picture on a national scale, where FareShare locations and other redistribution efforts remain fragmented and independent of each other. A similar picture is seen in the case study of project Roomkey in section 3.2. Evidence of mismatches, unfilled rooms despite higher numbers of unhoused persons, and 30% success rate could all be attributed to adoption of local matching producers over a core allocation overseen by the city of LA. Below we offer a summary of recommendations for surplus redistribution of essential resources like food, clothing, and housing.

4.1.1 *Recommendations for surplus redistribution.*

- *Existence of a third party redistributor.* This is necessary for a core allocation and perhaps why organizations like FareShare and Feeding America have been more successful than smaller independent efforts.
- *Government policy.* The core redistribution is easiest as a national government undertaking otherwise there needs to be policy to regulate and protect the operations of the third party redistributor and producers, in terms of liability, tax write-offs, and subsidies to fund the cost of redistribution.
- *Investment in supply and demand predictions.* Evidence from the case studies showed that a healthy knowledge of how much surplus for redistribution, and how much demand for the surplus there is, are key to successfully minimizing waste and maximizing welfare.
- *Creation of awareness.* Lastly, there has to be considerable effort put into making the public aware of the existence of these core redistributors and the benefits of redistributing surplus through a core redistributor.

4.2 Limitations

There are factors beyond locality that affect surplus redistribution that are not considered here, the biggest of those being the politics of welfare efforts. Policy and government intervention is key for surplus redistribution and waste minimization, but there is rarely sufficient support of that nature.

Additionally, the claim of zero or nearly zero value of surplus at the end of a production or supply cycle ignores value outside profit, like social value from donating surplus, feeding employees, or any other forms of value. However, we believe considering these other forms of value beyond profit does not have significant effect on the model proposed here.

The text also assumes that donation centers consider waste reduction a priority, but that is not always the case because some donation centers only care for satisfaction of their demand and growth. Both of which are affected by waste reduction, but that is not always obvious to local donation centers. This text also assumes that a third party, like, a federal or local government would avail funds for the cost of redistribution. Future work could explore how a network of donation centers would collectively cover this cost and what that would mean for their utilities.

Another limitation is that this text doesn't properly address the definition of surplus or what is considered waste. Evidence from the UK food waste case study shows that confusion between "best by" and "use before" labels is one of the biggest sources of waste creation. That issue and others related to definition or categorization of what is surplus or waste have not been addressed in this text because those definitions are domain specific and this text is meant as a general guide for surplus redistribution.

Lastly, multiple reports showed that the largest proportion of consumer waste is created by households, but this research only looks at redistribution of surplus from producers. Perhaps future work could investigate and propose solutions for redistribution of surplus accumulated by households.

4.3 Open Problems

4.3.1 Individual rationality in the absence of government funding. **Research question:** *For any arbitrary donation center, would the cost of joining a network of donations centers that run a core redistribution of surplus and cover the cost of redistribution be less than the cost of seeking local independent donations out of network?*

This is the question of individual rationality specifically for donation centers in affluent neighborhoods where donations may be in plenty. If we imagine the worst case scenario where there is no funding from a government or third party donor to cover the cost of redistribution, would it still make sense for donation centers to merge resources and run the core redistribution because the cost of being in the core(in the network) would still be less than the cost of being out of the core (out of network). This is still an open and important question.

Intuitive Speculation: Since a core redistributor would guarantee minimal amount of waste at each donation center, the absence of a cost of waste management for each donation center could offset the new contribution to the cost of redistribution. Additionally, other benefits from a core redistribution like standardization of donations could also alleviate other operational costs for each donation center that would justify joining a network of donation centers. However a mathematical proof to show these cost offsets is required to properly answer this open question.

4.3.2 Capacity of a core redistribution network. **Research question:** *What is the geographical upper and lower limits and user capacity constraints required for a core redistribution to achieve the proven benefits over local independent donation mechanisms?*

Phillips et al. [2013] gives some numerical bounds on the capacity constraints and geographical limits that have to be met for a core redistribution to become beneficial interms of cost of redistribution and waste created. To the best of our knowledge, theoretical proofs of these bounds have not been put forth anywhere in the literature. So questions like, how many localities can a core redistributor cover while still achieving minimal waste, and also meeting all the donation centers' demand?

Intuitive Speculation: The core redistribution proposed here has constraints to minimize waste while maximizing welfare, specifically satisfying demand. One could imagine applying the same mechanism and proof with an added constraint of minimizing costs of transportation. Intuitively, the transportation cost constraint could allow for effective redistribution over a large collection of localities. However it is not trivial to determine how that would affect waste and welfare, for example in a network with both dense and sparse localities. Theoretical or empirical investigation is required.

4.3.3 Strong preferences. **Research question:** *How would strong preference on the donations from donation centers affect the core redistribution?*

Consider the scenario where donation centers specifically prefer certain items over others. How these strong preferences would be met is not accounted for in the core redistribution. It therefore remains an open question how the existence of strong preferences would alter the core redistribution.

Intuitive Speculation: The modification for multiple bundles given here could be sufficient to cater for strong preferences as they would be reflected in the quantities demanded for each item from each donation center. However, while it seems intuitively the case, a proof is still required to show that a core redistribution would optimally meet every donation center's preferences on the items.

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