

Empowering Collective Impact: Introducing SWAP for Resource Sharing

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Nonprofit organizations (NPOs) lack resources, hindering the quality and quantity of service they can deliver. Meanwhile, NPOs at times have underutilized or even spare resources due to the inability to scale expertise in staffing and tangible resources to meet temporally shifting service demands. These observations motivate us to propose a novel resource sharing system, *SWAP*, which to the best of our knowledge, is the first resource sharing system that facilitates resource exchanges where NPOs can obtain resources by offering their own. *SWAP* consists of four elements: a collaborative auction-based sharing process, complete with offering and bidding mechanisms, and the virtual currency, *SWAPcredit*, to facilitate liquidity in exchange; a central technology that represents the award determination problem with a multilateral exchange optimization model, generating resource exchange outcomes; an online platform, the *SWAP Hub*, where NPOs can execute offering and bidding, and receive exchange results; and human-centric co-design, shaping the understanding and design decisions of a research collective, that includes the authors and NPO professionals. We conduct a series of experiments using both empirical and simulated data to illustrate the benefits and potential of *SWAP*. Our results demonstrate that *SWAP* can address temporal resource needs in practice; show that optimal exchange outcomes can be generated even for large-scale *SWAP* markets; and provide strong evidence in support of guidance to inform the progression for future versions of *SWAP*. The *SWAP* system is presently implemented in Howard County, Maryland, USA, with ongoing enhancements and potential for future expansion.

CCS Concepts: • **Applied computing** → **Operations research**; *Law, social and behavioral sciences*.

Additional Key Words and Phrases: Market Design, Auctions in Practice, Resource Allocation, Integer Optimization, Nonprofits

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1 INTRODUCTION

Nonprofit organizations (NPOs) provide services to tackle critical societal problems, particularly ones affecting vulnerable populations [18]. The nonprofit sector does this by employing the third largest workforce in America with 12.5 million jobs [37] and relying on a large volunteer base; 63 million Americans volunteered an average of 3.5 hours per week [14, 17]. Acquiring resources is their top challenge [10, 22]: 86% of nonprofit leaders indicated an increase in demand for their services, yet, 57% conveyed they could not meet the demand, with this number increasing to 65% for NPOs serving low-income communities [22]. Demands placed on physical resources, technology, and skills *fluctuate over time*,

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leading to temporary differences in how NPOs value resources. This results in a paradox: at times resource-scarce NPOs underutilize resources due to the inability to easily mobilize staffing and tangible resources to meet temporally shifting service demands. This paradox was confirmed in a preliminary study we conducted with a set of NPOs in Howard County, MD [25], where each nonprofit leader shared available resources and internal valuations, as well as needed resources and valuations. For instance, one NPO was willing to lend a coordinator, and needed a Spanish-language translator. Another NPO had a Spanish-language translator to offer but needed social media help. Yet without a way to elicit needed resources (*needs*) and see temporally available resources (*haves*), nor a fair and easy approach to facilitate an exchange, these resources sat underutilized. An opportunity clearly exists to design a system to facilitate resource sharing among nonprofits and empower collective community impact.

A conventional way that nonprofits might attempt to identify available resources and exchange resources is checking with one or more NPOs in their professional network, until obtaining the resource for the desired time and duration, or else resigning. This process is 1) time-consuming, 2) may require significant effort and negotiation, 3) limited by the size and strength of the NPO's professional network, and 4) likely dependent on the sequential nature, all of which reduce the likelihood of successful resource sharing and limit the collective potential in the network. Moreover, the conventional negotiation process between two organizations carries an implicit assumption of a one-for-one exchange of resources that are equally valuable, when in reality some resources have higher utility than others: the value of using a minivan for an hour is likely greater than the value of using a projector and screen kit for an hour.

Nonprofits can save time and effort by considering alternative mechanisms for resource sharing. While the Sharing Sugar approach [7] advocates for exchanging resources between organizations by minimizing the total remaining expressed cost (utility) that cannot be matched to any available resources, in practice no technology exists to facilitate such exchanges. We propose a resource sharing system for nonprofits called *SWAP*. The system has four elements: an auction-based sharing process with an offering mechanism, a bidding mechanism, and the virtual currency, *SWAPcredit*, to facilitate liquidity in exchange; a central technology that represents the awarding determination problem with a multilateral exchange optimization model, upon solving optimal exchanges of resources; the *SWAP Hub* where NPOs can post and bid on resources and receive exchange results, functioning as an online platform for the *SWAP* sharing process; and human-centric co-design, shaping the understanding and design decisions of a research collective, that includes the authors and NPO professionals to ensure NPOs' voices are heard and *SWAP* is kept improving all the time.

We make the following contributions. First, we introduce an auction-based mechanism for sharing resources, deployed in the nonprofit sector. We believe *SWAP* to be the first resource sharing system that facilitates resource exchanges, *where entities can obtain resources by offering their own*. *SWAP* amplifies the opportunity and potential to exchange available resources for needed resources, thereby providing an ideal means for NPOs to obtain resources. With an auction mechanism and virtual currency at its core, our resource sharing process has been intentionally designed to be both user-friendly and easily scalable, meeting the needs of NPOs seeking efficient and effective resource sharing. Second, we introduce an integer optimization model to clear the market, representing the exchange and (re)allocation of resources to maximize the total valuation differential of bids and asks so as to benefit participating nonprofits as a collective. The formulation itself encourages NPOs to offer resources, as the more an NPO offers resources at reasonable values, the more likely they will be exchanged, enabling the NPO to acquire needed resources. Third, we introduce the online *SWAP Hub* platform that facilitates resource sharing by allowing each NPO to easily post and bid on resources, and receive exchange results. Fourth, through experiments with empirical and simulated data, as well as via an active and ongoing pilot with small-median nonprofits in Howard County, MD, USA, we reveal the potential for *SWAP* to play an important role in fulfilling temporal resource needs of nonprofits. Empirically, we show that NPOs are

willing to share their resources; NPOs that want more resources tend to offer more resources; and there is reasonable alignment between what NPOs have to share, and what NPOs need. Through simulation, we observe that SWAP can efficiently compute optimal exchanges for larger-scale markets of even 100 NPOs; the greater engagement by NPOs to offer resources can both promote more exchanges collectively, and for NPOs individually; and under high levels of competition, we highlight opportunities for time-based offerings to moderate the competition.

The study proceeds as follows. Section 2 covers relevant auction and matching designs. Section 3 details the SWAP system and its multilateral exchange optimization model. Section 4 discusses our human-centric co-design for collective community impact in practice. Section 5 presents extensive computational experiments including real and simulated data to highlight key insights into the design of the SWAP system for nonprofits. Section 6 concludes.

2 BACKGROUND AND RELATED WORK

We investigate recent studies about auctions and matching markets for the nonprofit sector, with an emphasis on mechanisms that have been deployed in practice.

A notable instance is the auction market at Feeding America [29]. A new market, the centralized allocation mechanism called the Choice System, addressed the unequal distribution of food across food banks and time-consuming matching between donors and food banks [29]. Another famous example details how exchange market and currency are formed in a Prisoner of War (POW) camp, where cigarettes (homogeneous, durable, and of convenient size) were used as a common commodity to facilitate negotiations and reallocations of goods [30]. Chakraborty and Zhao propose an auction-based resource exchange network to promote community cooperation based on a Vickrey mechanism and a credit mechanism to reward communities where communities accrue more credits as their number of winning bidders increases [11]. Course Match processes student course preferences, budgets, and course target and capacity, and computes a clearing price for each course at an approximate competitive equilibrium [9]. Bichler et al. design three bidding languages, demand–supply constraints, and quadratic optimization models for the catch rights of fish by carefully considering two seller statuses, institutional restrictions, and subsidy distribution [6]. The exchange in 2017 demonstrates the effectiveness and fairness of the transfer of catch shares from inactive to active fishers [6].

Distinct from auction markets, matching markets are those where prices do not play the dominant role [31]. College admissions is the basic problem of two-sided matching between colleges and students: articulating preferences and identifying a match that satisfies both parties [23, 35, 36]. Refugee resettlement considers the matching of refugee families to communities in the designated country where they can resettle safely with autonomy and independence. [3, 4, 12, 16]. An objective of refugee resettlement is to optimize refugee wellbeing (through indicators such as employment) in host communities [3, 4]. The focus of the classical school choice problem is matching students to schools by resolving two long-standing challenges, multiple schools always giving offers to the same small group of students, and students feeling unsafe to report their true preferences [1, 2, 26]. Implementing the deferred acceptance algorithm in real high school matches in New York City and Boston significantly reduced the number of students who did not receive offers from their preferred schools [2, 23, 26]. Given student preferences over project centers, academic performance, and required skill sets by project centers, an optimization-based framework that maximizes total placement and total preference, has been used since 2017 to annually allocate over one thousand students to global project centers at Worcester Polytechnic Institute [41]. The New England Program for Kidney Exchange (NEPKE) identifies efficient combinations of feasible kidney exchanges and design optimal matching mechanisms for transplantation [32]. NEPKE made 50% more matches by expanding from bilateral to multilateral exchange mechanisms [33, 34], and the further dynamical model that factors in time cost and future exchange opportunities maximizes the total discounted exchange surplus [40].

Due to changes in funding climate and resource challenges [21, 22], in recent years NPOs have begun to design, experiment, and practice certain forms of collaborations to reduce competition for resources [13]. Yet, research on NPO collaboration and its assessment, as well as mechanisms to facilitate NPO collaboration, have seen less attention in the literature [24]. To the best of our knowledge, no general mechanism exists for resource sharing among nonprofits. Thus, our study contributes by proposing a new form of nonprofit collaboration from the perspective of resource exchange.

3 THE SWAP SYSTEM AND MATHEMATICAL MODELING

In this section, we formally introduce the specifics of the SWAP system and describe the resource exchange problem and the multilateral exchange optimization model.

3.1 The SWAP System

Our team met with NPOs for more than two years for design, development, user-testing, and deployment of SWAP. The success of this innovation depended upon myriad tweaks and additional institutional details needed for both buy-in from the relevant constituents and reflected important considerations on the ground. We consistently relied upon NPO directors and staff to provide feedback on SWAP's design and deployment. Our main objectives were to create auction-based resource exchange markets with straightforward offering and bidding mechanisms, exchanges generating collective impact, an atmosphere of fair participation, and ease of deployment. In the next subsections, we introduce the components of the SWAP system that work together to achieve these objectives.

3.1.1 Nonprofit Cohort. The SWAP system may contain any number of independent SWAP markets, each consisting of a group of nonprofits (called a *cohort*) where sharing processes (called *episodes*, see Section 3.1.3) are scheduled and conducted independently. An NPO interacts (e.g., offering, bidding, matching, exchanging) only with NPOs in the same cohort. A cohort would most commonly be formed by a group of nonprofits located in the same metropolitan area, or commuting zone, as such proximity to each other is necessary for resource exchanges. Yet, if a group of NPOs only shares remote talents and skills, a cohort formation is possible without the aforementioned geographical restriction.

3.1.2 Distribution of SWAPcredits. SWAPcredit is a virtual currency used within the SWAP system to capture and reflect the preferences (utilities) of NPOs. SWAPcredit can only be used for bidding on resources, and has no value outside of the SWAP system. In a newly formed cohort, the SWAP system firstly allocates SWAPcredits to each NPO within the cohort. Each NPO receives an equal endowment of SWAPcredits as their balance for each episode use, thereby promoting fairness by ensuring all participants start at the same place. In the absence of the designs of SWAPcredit and the equal balance, NPOs with more real capital (e.g., more money with the greater ability of fund raising) could consistently outbid others for resources, while other organizations may struggle to raise sufficient capital to bid. The actual number of SWAPcredits is adjustable, and a SWAP committee (see Section 4.1) organizes practice episodes and reviews feedback from NPOs before formally implementing an allocation method for any individual cohort.

3.1.3 Episode Steps and Episode Frequency. A sharing process (called an *episode*) is comprised of a single offer round, a single bid round, and then a market-clearing exchange of resources takes place to determine those that were awarded resources, followed by the results being published and real exchanges happening. Upon the offer round beginning, each nonprofit has a representative log into the SWAP Hub, an online platform that was created and deployed in practice, to post temporarily available resources with resource descriptions, time availability, and proposed ask values as *offers* (see Section 3.1.4). The bid round begins after the offer round closes, allowing nonprofits to bid on desired resources that have been offered by others using SWAPcredit as *bids* (see Section 3.1.5). When the bid round closes, all bids on all offered resources are known, and the integer optimization technology (Section 3.2) is used to find the market clearing

optimal resource exchange that maximizes the total valuation differential between bids and asks. The results are then published in the SWAP Hub for NPOs to know what they are giving and receiving. After that real exchanges happen among NPOs in the same cohort, with NPO's rights and obligations for giving and receiving resources described in a cosigned collective agreement (see Section 4.2). Episodes are conducted sequentially. Based on each cohort's practical demand, this could result in biweekly or monthly exchanges, but at scale could conceivably be much shorter (weekly), as long as the exchanges can reasonably take place.

3.1.4 Offering Mechanism. A reasonable number of offered resources is important for the health of the SWAP market. A resource, typically a physical resource or a human resource requiring mobilizing, that is available for multiple consecutive days is guided to be split offers of a single or half day. The benefits of listing the same resource as multiple offers include opportunities for NPOs to earn SWAPcredits from multiple offers, and allows multiple NPOs to obtain these offered resources as bidders. At the same time, too many offers of the same resource with a short given time duration is undesired as it may raise issues about how to safely deliver physical resources or mobilize human resources. Thus, setting a hard lower bound on the minimum availability period avoids impractical, low quality offers. NPOs were instructed at the initial cohort training on how to offer resources that are either specific or flexible in time, allowing greater freedom in determining the actual exchange period. A SWAP committee (see Section 4.1) meets regularly to review NPO feedback and comments to adjust needed restrictions.

3.1.5 Bidding Mechanism. All bidding occurs under sealed bids. The sealed bid design counters concerns about bid shielding and sniping that can occur in online auctions where the bidding close time is public knowledge [39]. In the context of SWAP, larger NPOs could potentially dedicate staff to observe the bidding behaviors of others, and enter a desired bid value and an excessively high bid value which is retracted at the last moment to deter other participants from continuing to bid or directly snipe at the last moment to submit the highest bid, placing smaller NPOs with fewer employees at a possible disadvantage. SWAP is intentionally designed as a first-price auction where an awarded NPO is the one that places the highest bid value as long as they can afford the resource at their placed bid value. For NPOs, the first-price auction is clear and straightforward and minimizes strategies played. A salient feature of SWAP's bidding mechanism is that it allows NPOs to bid more than their current SWAPcredit balance; this is because by offering resources (that are wanted by other NPOs) can increase their SWAPcredits.

3.1.6 Mathematical Modeling. Given offering and bidding information for any episode, the problem of determining the multilateral exchange uses integer optimization to maximize the overall exchange efficiency reflecting the gains from swapping that accrue to all participants. Mathematical preliminaries are introduced first. This mathematical problem considers two sets: let $\mathcal{N}$ be the set of participating nonprofits, indexed by i, j ; and let $\mathcal{R}_i$ be the set of resources offered by nonprofit i , indexed by k . The identified parameters are c_i as SWAPcredit balance of nonprofit i , r_i^k as ask price that nonprofit i sets for resource k , and $b_{i,j}^k$ as bid price that nonprofit j proposes for resource k of nonprofit i . Finally, the set of binary variables is defined as $x_{i,j}^k$; equal to 1, if nonprofit j receives resource k of organization i ; 0, otherwise; $j \neq i$.

The multilateral exchange optimization model¹ determines the optimal exchanges through maximizing the total differential between bid values and ask values of exchanged resources (i.e., $x_{i,j}^k = 1$) (1a). The first set of constraints (1b) ensures that each offered resource may be exchanged at most once. The second set of constraints (1c) upholds the SWAPcredit restriction that shapes how resources are awarded, thereby incentivizing the offering of resources. The

¹Instances of (1), whether real or simulated, may have multiple optima. Deterministic solvers such as [19] traverse the same solution path, resulting in the same optimal solution. To counteract, we create a pre-optimization mapping that assigns each participant a shuffled new index before optimization, giving each multiple optima an equal likelihood. This method can serve to distribute any unmerited favor among all NPOs over time.

constraints allow each NPO to be awarded any resource that they can afford—the credit balance, c_j , plus any incoming credits from offered resources that are exchanged, $\sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{R}_j} b_{j,i}^k x_{j,i}^k$. The balance, c_j , serves the critical role of ensuring the possibility of exchanges. Without balances ($c_j = 0, \forall j \in \mathcal{N}$), no net gains are possible for any participant ($\sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{R}_j} b_{j,i}^k x_{j,i}^k - \sum_{i \in \mathcal{N}} \sum_{k' \in \mathcal{R}_i} b_{i,j}^{k'} x_{i,j}^{k'} \geq 0$). More broadly, constraint set (1c) plays a critical role in promoting both the supply and demand sides to maintain sufficient market liquidity.

$$\text{maximize} \quad \sum_{j \in \mathcal{N}} \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{R}_i} (b_{i,j}^k - r_i^k) x_{i,j}^k \quad (1a)$$

$$\text{subject to:} \quad \sum_{j \in \mathcal{N}} x_{i,j}^k \leq 1 \quad \forall i \in \mathcal{N}, \forall k \in \mathcal{R}_i, \quad (1b)$$

$$\sum_{i \in \mathcal{N}} \sum_{k' \in \mathcal{R}_i} b_{i,j}^{k'} x_{i,j}^{k'} \leq \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{R}_j} b_{j,i}^k x_{j,i}^k + c_j \quad \forall j \in \mathcal{N}, \quad (1c)$$

$$x_{i,j}^k \in \{0, 1\} \quad \forall i, j \in \mathcal{N}, i \neq j; \forall k \in \mathcal{R}_i. \quad (1d)$$

4 HUMAN-CENTRIC CO-DESIGN

To align SWAP with the ethos of the NPOs, we employ a value sensitive design (VSD) framework [20], which considers human values throughout the design process. The SWAP research collective (of which the authors belong), from inception, led an intentionally generative and iterative process, seeking engagement across design decisions, assessments, and refinements. While VSD is primarily a way of ensuring that technology innovation leads to greater good and lesser evil, it can facilitate a relationship between designers and stakeholders that becomes the basis of a co-design process. Informed by VSD, the co-design process integrates ethical and technical imagination to ensure that SWAP becomes a tool that genuinely benefits NPOs and the communities with which they work.

4.1 Interdisciplinary SWAP Research Collective and Action Oriented Research

The SWAP research collective consists of three social scientists, three operations research scientists, one nonprofit specialist, and one project coordinator working together as integrative co-researchers. Weekly meetings ensure that the team is communicating, sharing, thinking together, and influencing the design of each aspect of the research. The social scientists lead action-oriented research through interviews, surveys, and participant observation. By prioritizing collaborative reflections on the processes, procedures, and policies of SWAP, our action-oriented research models a symbiosis of knowledge generation and community action [38]. An open flow of information ensures research findings are frequently shared with participating NPOs. This helps stakeholders make informed decisions about design questions related to SWAP. These collaborative reflections focus not only on the practical aspects of SWAP (e.g., user interface, language used in instructions), but also on the alignment between SWAP and NPOs' conduct of mission-driven work.

When technology is built as a sole solution, outside of community voice, the end result is a product that alienates, rather than serves [15]. For the SWAP collective, technological intervention is only meaningful and effective when it closely aligns with the goals and values of the community [28]. To accomplish this, the team developed a mixed methods approach in which qualitative data is used to refine and guide interpretation of the quantitative data that emerges from NPOs' participation in SWAP exchanges. As NPO behaviors may not be fully captured by quantitative data, qualitative data helps ensure that individual NPO voices are fully heard in the research and development process.

4.2 Collaborative Agreement for Self-governance

One concern with algorithm-based platforms is participants feeling disconnected from each other despite shared resources and talents [8]. To address this, we decided to foreground SWAP with a shared understanding of collaboration

and cooperation. We co-created a charter document that laid the foundation for our community norms. From October 2022 to March 2023, our research collective, the participating NPOs, and a legal expert met to discuss and define the rights and obligations of each SWAP participant. As each NPO is both a giver and receiver, the meeting discussions highlighted reciprocal relations as the basis of SWAP. NPOs also wanted the agreement to address issues of liability and trust during resource mobilization. The SWAP agreement, covering participation, sharing, collective management, and conflict resolution, is based on three principles: a **collaborative spirit** that prioritizes sharing resources; a **need for flexibility and understanding** in achieving collective value; and **prioritizing staff safety and wellbeing** by creating opt-in opportunities for growth, learning, and networking that align with individual staff interests.

The first principle reflects the central value of SWAP: commitment to community. The second and third principles emerged from our initial engagement with NPOs. NPOs shared that because of resource limitations, they often have to temporarily change their work arrangements. Such changes can be a challenge to scheduled exchanges. Principle 2 emphasized trust as critical to building a resilient SWAP cohort that can weather these challenges. The third principle is a reflection of the cohort's concern for all participants, as NPOs' were initially skeptical of algorithm-based platforms and impact on workers. Thus, the collaborative document articulates the commitment of SWAP to the informed consent, autonomy, safety, and wellbeing of individual workers. Our intentional community-building and collaborative design intended to support feelings of belonging, reduce the potential for exploitation, and increase shared accountability.

4.3 Deployment

The deployment process was guided by our VSD approach. The first SWAP cohort was formally established in Howard County, MD, in August 2022. Since then, we have been working with the cohort members on various tasks: writing of the collaborative agreement, iteratively designing the SWAP Hub user interface, and finalizing the cadence of episodes. The first episode of SWAP launched in April 2023 after all cohort members signed the collaborative agreement and registered in the SWAP Hub. As the SWAP cohort grows, we expect our human-centric co-design approach to improve the entire SWAP system, facilitating increasingly complex exchanges.

5 EXPERIMENTS WITH EMPIRICAL AND SIMULATED DATA TO VALIDATE SWAP

This section presents a variety of experiments encompassing four goals: 1) improving our understanding of the characteristics of the resource sharing decisions of NPOs participating in resource sharing markets by analyzing empirical data, 2) identifying the performance of SWAP exchanges versus two baseline approaches using empirical data, 3) exploring the impacts of different offering and bidding behaviors on a sharing market through simulated data, and 4) demonstrating the computational efficiency of the multilateral exchange optimization model on small to larger-scale markets using simulated data. Section 5.1 introduces empirical data collected from three activities at an in-person event on March 17th, 2023 (NPO031723). An exploratory data analysis aligning with Goal 1) is then presented. Section 5.2 summarizes the outcomes from NPO031723 datasets, regarding the comparisons of SWAP and two baselines regarding Goal 2). Section 5.3 details simulated data generation and discusses the factorial experiments for Goals 3) and 4).

5.1 Empirical Data Experiment Design

This subsection introduces the empirical data collected from the SWAP event (NPO031723) and discusses the major observations from exploratory data analysis.

5.1.1 Empirical Data Collection. The SWAP in-person event took place on March 17th 2023 in Howard County, MD, USA. Twenty-one directors and staff from fourteen different NPOs were in attendance. The event leveraged participatory activities to encourage greater interaction among attendees and foster a greater understanding of the SWAP system, while enabling us to collect data on their behavioral patterns and characteristics.

The first datasets (NPO031723-AM) we collected were from an asset mapping activity. This activity increased the awareness that many useful assets (resources) exist among NPOs, and by having participants map resources their organization has and is willing to share is effective for identifying resources [5]. This activity inspired NPOs to broadly consider their shareable assets in three categories: physical resources, talents and skills, and subscriptions and memberships. Each NPO brainstormed and recorded their results in a worksheet. We collected all the worksheets to generate NPO031723-AM datasets that contain the resources from each NPO. One nonprofit director's voice carried weight and was likely a fair representation: "Initially, I thought we had few resources as we only have two staff; the activity really opened my mind; NPOs do not always need something large; many times just a small favor, like assisting with event planning or administrative work experience for short periods can really benefit others, so in this sense, I can see my NPO has many different resources." These encouraging words give our research collective increased confidence and motivation as NPOs not only seek resources, but also are willing to reflect on their own shareable resources.

The second datasets (NPO031723-GE) we collected were from a "green envelope" activity. Before the activity started, every NPO received a zipper bag containing four green envelopes, each with an enclosed index card, and 100 chips, all of which were uniquely labeled for each NPO. Fourteen NPOs were randomly separated into two equal groups, named Group A and Group B. Each NPO was allowed to interact only with people and activity items within their own group. The first step asked each NPO to select four resources from their asset mapping worksheets, write down one resource name per green envelope as an offer, and also write down it on the enclosed index card. The green envelopes were placed in full display on one of two whiteboards, one for each group. In the second step, let NPOs browse these offered resources to consider what they might need. NPOs were instructed to use chips to represent their preferences for a resource, which we considered as one's utility of obtaining a resource. Given 100 chips in total, each NPO placed chips into the envelopes of desired resources, with more chips corresponding to more highly desired resources. The envelopes were not transparent, preventing anyone from observing the number of chips placed by others, similar to a sealed bid approach. The NPO031723-GE datasets include data about who offered what and preferences over offered resources.

The third datasets (NPO031723-CS) were generated from a conventional sharing activity. The goal of this activity for each NPO was the same—to obtain resources they need from others through conventional negotiation. Nonprofits maintained in the same groups from the previous activity. Given six minutes, the two groups independently started within-group discussions. If a certain number of NPOs reached some agreement after negotiating, they exchanged their own index cards as described in the previous activity, which represented resources given, and received, among those NPOs. The only distinction between the two groups was NPOs in the Group A were restricted to one-on-one, pairwise conversations, while NPOs in Group B could simultaneously have many-way interactions. The purpose was to provide Group B with an opportunity to possibly conduct multi-way exchanges, while Group A NPOs would likely complete one- or two-way exchanges. The activity closely mirrored the conventional lending and borrowing process that occurs in the real-world. The NPO031723-CS datasets record, for every exchanged resource, the giver and the receiver.

The personal information and NPO profiles for all participants were kept confidential for all collected data. No identifying information was used during the data analysis. We have Worcester Polytechnic Institute (WPI) Institutional Review Board (IRB) approval (Record #: IRB-23-0010), and all attendees signed consent forms prior to participation.

5.1.2 Exploratory Data Analysis on Empirical Data. After cleaning the data and examining for outliers, our exploratory data analysis objective was to identify patterns and relationships within the datasets to better understand the characteristics of the decision behavior of the NPO participants. Our first observation is that NPOs naturally may maintain a certain level of balance of haves and needs. Figure (1a) displays the count of resources each NPO (represented by a

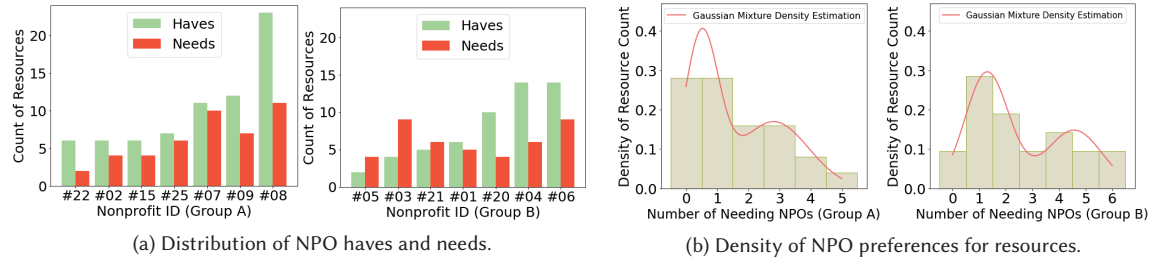


Fig. 1. Empirical data analysis of hases-needs relationship and resource preference frequency.

Table 1. Count of offered resources for each NPO receiving chips from other NPOs within a group.

	GroupA							GroupB							
Nonprofit ID	#09	#15	#07	#08	#25	#02	#22	#06	#01	#05	#07*	#20	#04	#03	#21
# of Resources Offered	4	4	3	4	4	2	4	3	4	1	1	1	3	4	4
# of Resources with Chips	2	2	2	3	3	2	4	2	3	1	1	1	3	4	4

* NPO #07 inadvertently offered three resources in Group A and one resource in Group B. Accordingly, NPO #07 also appears in both groups in Figure 2 and Figure 3.

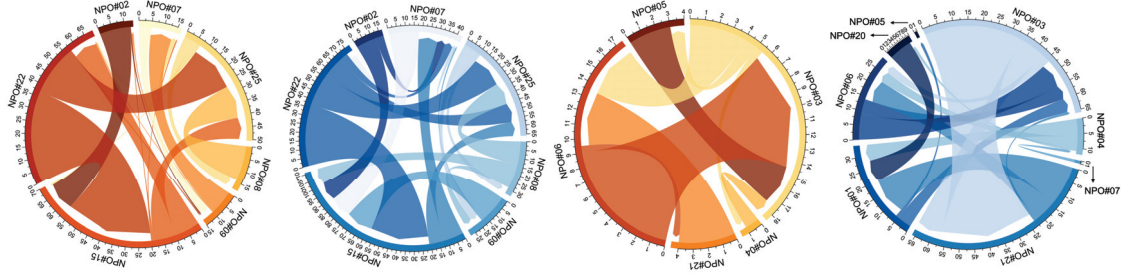
unique ID) has and the count of resources each NPO needs in the two groups. NPOs with a greater number of available resources tend to also have a greater need for resources. These patterns suggest a foundation exists for establishing SWAP sharing markets as all NPOs are able to share resources with others. If an NPO wants more resources, they are also capable to offer more resources.

The second observation is that in both groups, every NPO receives chips from others on at least a portion of their offered resources listed on their green envelopes. The number of resources each NPO offers and the number of resources receiving chips are listed in Table 1. While some NPOs are unable to select four resources as offers within the allowed six minutes, it is evident that each NPO has at least 50% of their offers in demand by other NPOs in both groups; and 72.0% and 90.5% of offers are needed on average, respectively. This observation implies that there is a good level of alignment between what NPOs have to share and what NPOs need, which is critical for creating SWAP sharing markets.

The third observation is about the resource popularity represented by the multiplicity of NPO preferences for the same resource in a group. Figure (1b) presents frequency distributions for the number of unique chips received by a resource for each of the two groups, each NPO having uniquely labeled chips. For the two groups respectively, 28.0% and 28.6% of resources are needed by a single NPO, while 32.0% and 28.6% of resources are needed by two or three NPOs each; the remaining 12.0% and 33.3% of resources are needed by more than three NPOs. The two distributions reveal that resources are not equally desired by nonprofits; over 50% of resources experience relatively low levels of competition, whereas the remaining half are more popular and subject to varying levels of competition.

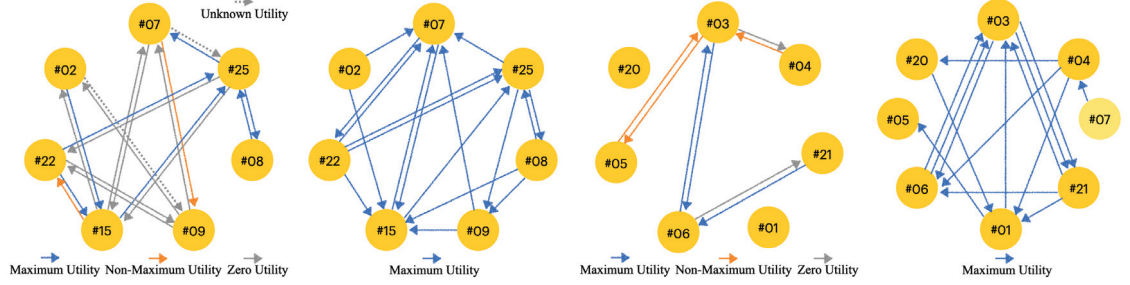
5.2 Experiments with Empirical Data

We conduct a set of experiments to compare the results of the SWAP exchange process with the performance of two baselines emulating the natural process NPOs would undertake to seek needed resources. The first baseline, B-CS, is the conventional sharing activity. The collected data, NPO031723-CS, contains the direct exchange results consisting of the index card exchanges among NPOs. The second baseline, B-GE, combines outcomes of the green envelope activity with a human central decision maker (CDM) role played by the lead author using utility information in collected data, NPO031723-GE, to determine final exchanges. The manual approach taken to determine resource exchanges was to



(a) Group A exchange utilities: B-CS (left) versus SWAP (right). (b) Group B exchange utilities: B-CS (left) versus SWAP (right).

Fig. 2. Comparisons of exchange utilities across two groups, between baseline conventional sharing and SWAP.



(a) Group A exchange behaviors: B-CS (left) versus SWAP (right). (b) Group B exchange behaviors: B-CS (left) versus SWAP (right).

Fig. 3. Comparisons of exchange behaviors across two groups, between baseline conventional sharing and SWAP.

maximize the total utility from matching available resources. The SWAP exchange process (SWAP) uses the same data, NPO031723-GE, entering green envelope resources and expressed utilities through the SWAP Hub to mimic resource offering and bidding rounds. In this context, the SWAPcredit balance of 100 is set to each NPO, mirroring the 100 chips given to each NPO; ask values are set to zero; and the sealed bidding is equivalent to putting chips into opaque envelopes without knowledge of what and how many chips were placed by other NPOs. These parameters instantiate optimization model (1), which is implemented in the PuLP Python modeling environment [27], to compute an optimal exchange through solving with the COIN-OR Branch-and-Cut (CBC) solver [19].

We first compare the three processes of seeking out needed resources. Conventional sharing has some shortcomings in that NPOs are initially expected to offer resources while they also lack access to view all available resources. The B-GE, in contrast, provides a shared avenue for viewing resources, while SWAP goes a step further through a shared, online platform that permits each NPO to browse all posted resources after offering their own, thus enabling NPOs to holistically assess how their own needs may be met. Another advantage that SWAP has over B-GE is the ask value feature, allowing NPOs to set minimum acceptable values for offered resources. Unlike SWAP, B-GE does not consider the earnings or the SWAPcredit restriction throughout constraints (1c), so there is no incentive for NPOs to offer resources with high quality and popularity. In B-CS conventional sharing, NPOs repeatedly ask for needed resources and negotiate with other NPOs. In contrast, B-GE and SWAP allow NPOs to express preferences as bid values for their needs, with CMDs generating final outcomes. Table 2 shows the time cost of CDM computing. While limited in scope, the time it takes SWAP

Table 2. Time for CDM to reach a completed exchange. By definition, B-CS does not reach a completed exchange.

	Time Cost (minutes)	
	Group A	Group B
B-CS	—	—
B-GE	31	33
SWAP	0.01	0.01

CDM to complete is more than four orders of magnitude less than B-GE. While for smaller-sized markets it is possible under B-GE to serve as a CDM and manually clear the market², such a process becomes increasingly complex and prohibitive as the market thickens with more participants, offered resources, and expressed utilities. While it also grows for SWAP, we have experiments that demonstrate the scalability of SWAP in Figures 7. We thus directly compare the final exchange results of B-CS with SWAP.

The exchange mechanism is what clearly differentiates B-CS and SWAP. Figure 2 and Figure 3 depicts exchange utilities and exchange behaviors among participants in Group A (left) and Group B (right), respectively. In Figure 2, each directed arc indicates an exchange from one NPO to another. The width of the arc at its destination, with values stated, indicates the utility obtained by a receiving NPO. By totaling the utility obtained by each NPO, the overall utility in SWAP is larger compared to B-CS in both groups. Moreover, the exchanges of B-CS are limited to bilateral exchanges, as shown by the presence of two complementary directed arcs connecting pairs of NPOs in Figure 3. And, while we observed the NPOs in Group B communicating in a multilateral manner, the resulting exchanges remained bilateral. Gray arcs indicate no gained utility from the returned resource of a bilateral exchange. As a result of these distinct exchange patterns, B-CS is only able to reach some feasible (and suboptimal) exchange outcome, denoted by the blue-gray, orange-gray, orange-orange, and blue-orange arc pairs. In contrast, SWAP is readily capable of uni-, bi-, and multilateral exchanges, achieving an outcome that globally maximizes the overall exchange efficiency.

5.3 Experiments with Simulated Data

In this section we investigate how various offering and bidding behaviors affect exchange results through simulated data. We explore how SWAP outcomes are affected by the offering behavior of participants. We vary the number of resources that NPOs offer, including a cautious and conservative level (L1) that may occur in early stages of a newly established cohort, as well as more generous level (L3). As NPOs become more experienced with offering resources, they tend to offer more and a greater variety of resources. We also explore the effect of NPOs placing fewer bids (L1) to more bids (L3) to simulate different bidding volume behaviors. We finally test the computational efficiency of solving the multilateral exchange optimization model to demonstrate its potential for deployment at scale. We hold all attributes constant and vary three factors independently: the number of resources offered by each NPO, the number of bids placed

²In fact, we did for this for our moderately-sized markets, attaining the same exchange results as SWAP.

Table 3. Three varied factors and levels in simulated data.

Varied Factor	Levels: L1, L2, . . .		
	<u>Low (L1)</u>	<u>Medium (L2)</u>	<u>High (L3)</u>
# of Resources Offered per NPO	$\Pr(X \in \{0,3\})=0.4^{**}$ $\Pr(X \in \{1,2\})=0.6$	$\Pr(X \in \{0,1,9,10\})=0.2$ $\Pr(X \in \{2,8\})=0.15$ $\Pr(X \in \{3,4,5,6,7\})=0.65$	$\Pr(X \in \{7,10\})=0.4$ $\Pr(X \in \{8,9\})=0.6$
	<u>Low (L1)</u>	<u>Medium (L2)</u>	<u>High (L3)</u>
# of Bids per NPO*	$\Pr(X \in \{R - 1, \dots, R + 2\})=1$	$\Pr(X \in \{R - 1, \dots, R + 2\})=0.5$ $\Pr(X \in \{R + 3, \dots, 2R\})=0.5$	$\Pr(X \in \{R + 3, \dots, 2R\})=1$
	<u>Levels L1 through L8</u>		
# of NPOs	5, 10, 15, 20, 25, 30, 35, 40		

*For defining the probabilities, let R denote the number of resources offered by the respective NPO.

**The probability that an NPO offers 0 or 3 resources is equal (discrete uniform), and likewise for other discrete variables in each level.

by each NPO, and the number of NPOs. Table 3 shows the designed levels of each factor. The controlled attributes, either constant or generated from a designated distribution³, appear in Table 4.

5.3.1 Effects of Number of Offered NPO Resources on Exchange Results. Table 4 provides the relationship between the number of resources offered by each NPO and the resulting exchange outcomes given all the other attributes held in their neutral states. This experiment assumes 10 NPOs of similar scale form a SWAP cohort, with each NPO having a total of 10 resources available to share in an episode. In Table 3, we consider three resource offering levels of “Low” where NPOs only offer zero to three of their 10 items, of “Medium” where NPOs offer from zero to 10 items, and of “High” where NPOs offer most of their items, from seven to 10. We run 10 replicates for each of the three levels.

Figure (4a) shows the distribution of the total number of exchanges by varying the number of offered resources, or the resource offering level. Varying the resource offering level across the three levels leads to statistically significant differences⁴ with p-value = 2.433×10^{-6} . Figure (4b) depicts the number of resources each participant receives through successful bids, by varying the resource offering level. With p-value = 8.473×10^{-43} , the resource offering level has a statistically significant effect on the number of resources received by each participant. This evidence supports that greater engagement and participation by NPOs to offer resources in a SWAP market could promote more exchanges for each NPO, and collectively. This supports the importance of increasing the awareness of their temporally available resources, such as by encouraging NPOs to embrace asset mapping as a tool to improve their resource awareness. As NPOs become more familiar with the SWAP market, its members, and its benefits, with intentional shepherding we anticipate increasing trust in the platform as a reliable source to acquire additional resources.

5.3.2 Effects of Number of Bids Placed on Exchange Results. We examine the effect of the number of bids placed on the resources exchanged. As detailed in Table 3, we vary the number of bids placed for three behavior types: low volume, medium volume, and high volume of bids placed. Table 4 details other attributes that are held constant and in their neutral states. In all levels of volumes of bids, NPOs have an equal likelihood of placing the number of bids within a range. For low volume behavior, the range of bids placed spans one less than the number of resources offered by the NPO, to three more bids than the resources they offered; for high volume behavior, the range spans from three more bids than the number of resources that NPO offered, to twice the number of resources they offered; the medium volume behavior combines the low and high volume behaviors, giving NPOs an equal likelihood of following the distribution of either behavior. We run 10 replicates for each of the three levels with 10 NPOs as a SWAP cohort in a replicate.

The distribution of the total number of exchanges for each bidding behavior level is shown in Figure (5a). First, we conduct a Kruskal-Wallis test for the difference between the total number of exchanges for each of the three bid volume levels. The test yields a p-value of 0.061, so we further conduct three pairwise Mann-Whitney U tests for more

Table 4. Controlled attributes in simulated data.

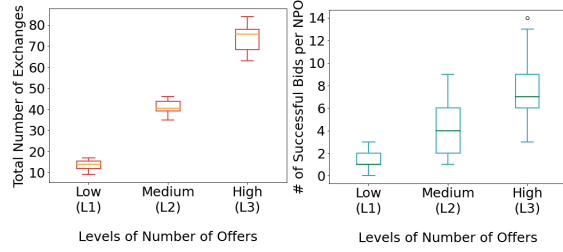
Controlled Attribute	Neutral Setting
Replicates per Run	10
# of NPOs	L2**
SWAPcredit Balance	50
Ask Value	$\Pr(X \in \{10, \dots, 24\}) = 0.6$ $\Pr(X \in \{25, \dots, 39\}) = 0.4$
Bid Value*	$\Pr(X \in [1.0r, 1.3r]) = 0.3$ $\Pr(X \in [1.3r, 1.6r]) = 0.4$ $\Pr(X \in [1.6r, 1.9r]) = 0.3$
# of Offers per NPO	L2**
# of Bids per NPO	L2**

*Let r denote the ask value of the respective offered resource.

**Factor level from Table 3 when the attribute is held.

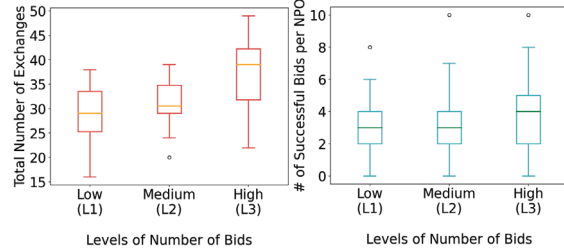
³Settings are based on the prior knowledge acquired from qualitative and quantitative data collected from meetings and events organized with NPOs.

⁴The assumption of i.i.d. is not met, so we apply the non-parametric Kruskal-Wallis test to compare distribution medians rather than means.



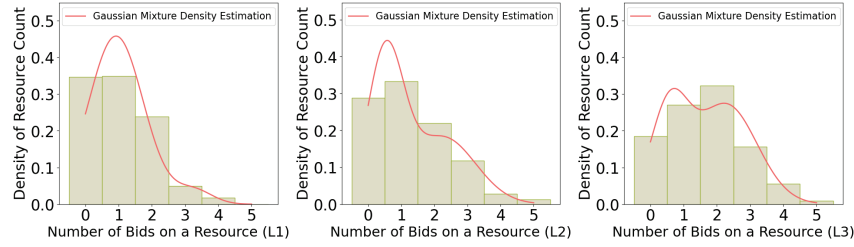
(a) Total number of exchanges across three levels. (b) Number of successful bids per NPO across three levels.

Fig. 4. Exchange results varying number of resources offered.



(a) Total number of exchanges across three levels. (b) Number of successful bids per NPO across three levels.

Fig. 5. Exchange results varying number of bids placed.



(a) Density of bids placed per resource. Low Volume (L1). (b) Density of bids placed per resource. Medium Volume (L2). (c) Density of bids placed per resource. High Volume (L3).

Fig. 6. Comparisons of number of bids placed per resource.

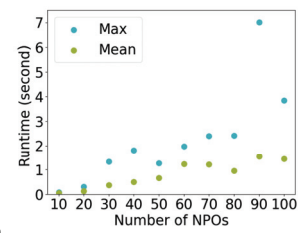


Fig. 7. Runtime for CBC solver to generate a solution for numbers of NPOs.

information. The p-value is 0.014 comparing the low (L1) to high (L3) bid volume levels; the p-value is 0.041 comparing the medium (L2) to high (L3) bid volume levels; and the p-value is 0.224 comparing the low (L1) to medium (L2) bid volume levels. This leads us to conclude that there is a significant difference in the number of exchanges when varying the volume of bids from low to high and from medium to high. Next, we look at the number of successful bids placed per NPO as the volume of bids increases, which is shown in Figure (5b). The Kruskal-Wallis test yields a p-value of 0.004 so we conclude that the different volume levels have a significant effect on both the success of bids placed for individual NPOs, as well as the collective of NPOs. As the volume of bids increases, the number of successful bids increases. While increasing the bid volume seems to have less of an effect on the number of exchanges than increasing the number of resources offered. In addition to the benefits from the increased volume of bids placed, there may be some downsides. While NPOs that are encouraged to bid more may have more bids awarded, a greater number of non-awarded bids may result in more disappointment. Moreover, although the sealed bid design of SWAP protects against bidding frenzy, greater competition for a specific resource only increases the number of needed SWAPcredits to be awarded the winning bid, which may negatively impact the sentiments of the NPOs and potentially discourage future participation. Thus, benefits need to be carefully balanced against any drawbacks, and suggest that increasing the number of resources offered may be a better alternative to increasing the number of bids placed.

To examine resource popularity, we test on the number of bids a resource receives when the volume of bids placed by each NPO is varied. For each of the bid volume levels, we plot the count of resources on the number of bids resources received (Figure 6). While these plots reveal that the number of bids per resource skews right, the number of resources receiving zero bids decreases as the bid volume level increases. We conduct a Kruskal-Wallis test for the difference between the number of bids received for each resource for each bid volume level. The test yields a p-value of 1.004×10^{-7} .

We conclude that there is a significant difference in the number of bids placed on each resource given different bid volume levels. Distribution of the number of bids a resource receives implies under higher volume bidding markets, a large percent of resources are needed by two or three NPOs. We can then advise NPOs to offer multiple time-based offers, providing more choices to NPOs who need the same resource, thereby helping moderate market competition.

5.3.3 Experiments of Computational Efficiency. To explore the scalability of the optimization solver solution, we conduct running time tests and vary the number of NPOs. We use the open-source mixed integer programming solver CBC (COIN-OR Branch-and-Cut) on an AMD Ryzen 5 4500U computer with Radeon Graphics, 2.38 GHz, and 10.0 GB RAM running 64-bit Windows 11. As the number of NPOs increases, the average runtime and the maximum runtime are shown in Figure 7. These runtimes reveal that the solver is sufficient for cohorts of very large sizes.

6 CONCLUSION

While NPOs face no greater challenge in fulfilling growing service demands than limited resources, the awareness that even popular internal resources are at times underutilized, highlights latent value. Given opportunities for NPOs to temporarily obtain available resources from other NPOs while sharing their own temporarily available resources, we propose *SWAP*, a sharing system, to facilitate resource exchange and to empower collective NPO impact. *SWAP* integrates a collective auction-based sharing process with an offering mechanism, a bidding mechanism, a virtual currency, and a multilateral exchange optimization model. *SWAP* is human-centric and co-designed by the research collective and participating NPO directors and staff. Analyses on data collected from real world experiments reveal that there is a general internal balance between the *haves* and *needs* of NPOs, and a good level of alignment between the *haves* and *needs* among nonprofits. This supports that the temporal resource needs of nonprofits can be partially met through *SWAP*. Through experiments on simulated data, we verify that *SWAP* can efficiently compute optimal exchanges even in larger-scale markets, and provides strong evidence of the value for increased asset mapping and resource awareness within the cohort, and for time-based offering strategies. The *SWAP* system is deployed with a first cohort in Howard County, MD, USA. Successful use of our online *SWAP Hub* platform, allows NPOs to easily post *haves*, provides access to view available resources and to bid on *needs*, and provides notification of the exchange results of both current and historical episodes. We have a legal expert and a team consisting of social scientists, operations research scientists, and nonprofit professionals to listen to the voices of NPOs and to integrate their feedback to improve *SWAP*.

The emergence of *SWAP* lays the foundation for exciting future research directions. While our empirical data experiments evaluated the *haves*, *needs* and preferences of real NPOs, future research may involve more participants to increase the diversity in characteristics that may lead to greater statistical significance. Broadening the empirical data collection to include more NPO participants in varying nonprofit ecosystems will reveal how this diversity manifests in *SWAP* exchanges. The formation of cohorts by considering NPO size, mission, and sector holds further promise.

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