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Shield-Net: Matching Supply with Demand for Face Shields During the COVID-19 Pandemic

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Abstract. The initial months of the COVID-19 pandemic were marked by widespread shortages of personal protective equipment (PPE) because of surging demand and a fragile global supply chain. In response, many domestic suppliers pivoted to producing PPE, such as masks and face shields, made possible by low material costs and simple designs. A key challenge that remained was the lack of an established marketplace for nontraditional suppliers of PPE to connect with healthcare facilities in need. To address this inefficiency, we launched an online platform, *Shield-Net*, to match requests for face shields with new suppliers of PPE. Our platform was based on an optimization model that produced supplier-requester pairs and took into account request urgency, request size, production capacity, location, and product type. During the period of March to September 2020, Shield-Net produced 390 matches, resulting in the shipment of more than 50,000 face shields to 68 unique requesting organizations. Supplier-requester proximity was found to be the only statistically significant variable in the success of a match. In this paper, we discuss the development and impact of our matching platform, as well as lessons learned during its operation.

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Introduction

One of the key challenges early in the COVID-19 pandemic was a global shortage of personal protective equipment (PPE), such as surgical masks, isolation gowns, and face shields. As early as March 2020, healthcare organizations in the United States reported difficulties in procuring sufficient PPE because of the sudden spike in demand (Kamerow 2020). A national survey revealed that 13% of healthcare facilities exhausted their face shield supplies, and nearly 40% of facilities were on the brink of depletion (Rebmann et al. 2021). By the first week of April 2020, approximately 90% of the PPE in the Strategic National Stockpile, the United States' emergency reserve of critical medical supplies, was expended through distribution to state and local governments (Biesecker 2020).

Because of the widespread shortage of PPE, public health experts began recommending new strategies for rationing and reusing PPE (Centers for Disease Control and Prevention 2020, Mahmood et al. 2020, World Health Organization 2020a). Despite these efforts, images of healthcare workers donning inadequate PPE began circulating in traditional and social media, with frontline healthcare workers calling attention to the issue with the hashtags #WheresMyPPE and #GetMePPE (Ankel 2020, Breen 2020, Ranney et al. 2020). The PPE shortage put first responders and healthcare workers at an increased risk of infection because of their exposure to COVID-19 patients (Nguyen et al. 2020, Ranney et al. 2020). Nguyen et al. (2020) found that healthcare workers in the United States and United Kingdom with insufficient PPE were significantly more likely to contract the virus, and a survey conducted in May 2020 showed that 27% of nurses caring for COVID-19 patients had been exposed to the virus without appropriate PPE (National Nurses United 2020). In addition to the increased risk of infection to frontline workers, a shortage of PPE may also compromise healthcare systems by reducing workforce capacity and eroding patient confidence (Castles 2020).

A silver lining to the PPE shortage was that the simplicity of certain PPE made it possible for nontraditional suppliers to quickly generate additional supply. For example, medical face shields can be produced using a small number of inexpensive components and tools of varying sophistication (UW Makerspace 2020). This simplicity in design allowed suppliers of all sizes to boost the total PPE supply by temporarily reallocating some of their production capacity to masks, face shields, and gowns. However, the procurement of this newly available PPE by healthcare facilities remained challenging. Many new suppliers of PPE were recent entrants to the PPE market, and healthcare organizations were not necessarily aware of their existence or how to procure from them. As a consequence, PPE shortages persisted among healthcare facilities despite the additional supply made available by nontraditional suppliers.

In this paper, we discuss the implementation of an online platform called *Shield-Net*, which we deployed in March 2020 to improve coordination between face shield buyers and sellers. The goal of our platform was to facilitate the distribution of face shields by matching nontraditional suppliers with organizations that placed requests for face shields in the system. At the core of Shield-Net is an optimization model that aims to produce matches in an equitable manner, accounting for request urgency, request size, production capacity, and geographic location. The platform was in operation from March to September 2020; during this period, the platform produced 390 matches, resulting in the confirmed shipment of 50,925 face shields to 68 unique organizations across the United States. The directory of face shield suppliers created for Shield-Net remains available online as of March 2021 (go.wisc.edu/k5thpt).

Our work belongs to a recent stream of literature on the development of automated tools for supporting the allocation of scarce resources during the COVID-19 pandemic. Most similar to our paper is the work by Bala et al. (2021), who discuss the matching platform GetUsPPE.org. In contrast to Shield-Net, GetUsPPE was entirely donation-based and matched other types of PPE (e.g., gloves, masks) in addition to face shields. Another distinction between our platform and GetUsPPE was the composition of the suppliers: in Shield-Net, suppliers were primarily manufacturers in nonhealthcare industries who switched production over to PPE, whereas suppliers on GetUsPPE were any individual or institution who had spare PPE they were willing to donate. Similar matching platforms were developed during the COVID-19 pandemic to coordinate laboratory equipment (Courcol et al. 2021), food boxes (Blackmon et al. 2020), and volunteers (Trautwein et al. 2020).

In the remainder of this section, we discuss the challenges faced by the traditional PPE supply chain during the COVID-19 pandemic, as well as an ad hoc PPE supply chain that emerged to address these challenges.

Traditional vs. "Pop-Up" PPE Supply Chain

The PPE shortage in the United States has been mostly attributed to weaknesses in the global supply chain. A reliance on outsourcing made the supply of PPE in the United States vulnerable to export restrictions that were imposed by major producers (e.g., China) at the start of the pandemic (Cohen and van der Meulen Rodgers 2020, Ranney et al. 2020). Additionally, an emphasis on lean manufacturing and just-in-time delivery has made suppliers more profitable but less able to respond to sudden demand spikes (O'Leary 2020). Other contributing factors to the PPE shortage included cost cutting by hospitals, insufficient emergency stockpiling of PPE by governments, and panic buying (Cohen and van der Meulen Rodgers 2020). Furthermore, the lack of a coordinated procurement strategy and limited market oversight led to procurement competition among buyers of PPE, as well as price gouging by sellers (Harwell 2020, Health Industry Distributors Association 2020, World Health Organization 2020b). Healthcare organizations that secured PPE still risked falling victim to extensive lead times (Health Industry Distributors Association 2020) and fraud (Feinmann 2020, Sternlicht 2020). These conditions disproportionately hurt small organizations (e.g., nursing homes, dental clinics) because of their minimal purchasing and bargaining power (Weber 2020).

Meanwhile, closures of nonessential businesses and a weakened economy led to a *surplus* of manufacturing capacity in nonhealthcare industries. Recognizing the opportunity to serve unmet demand for PPE, many U.S.-based suppliers retooled their production lines to accommodate PPE fabrication, thereby becoming short-term, domestic suppliers of PPE (Ford 2020, Fox 2 Detroit 2020, Ip 2020, Johncox 2020, Waxman and Reynolds Waxman 2020). This effectively created a parallel supply chain for PPE, which we refer to as the *pop-up PPE supply chain*, owing to the rapid and temporary entry of nontraditional suppliers into the PPE market. A pop-up supply chain is most closely related to research on supply chain disruption response and resilience, particularly temporary sourcing diversification, a strategy to briefly use alternate suppliers when a disruption occurs (Whitney et al. 2014). However, a pop-up supply chain differs in that the suppliers are new entrants to the market rather than existing, unused suppliers.

The pop-up PPE supply chain diverged from the conventional PPE supply chain in two ways: market concentration and distribution channels. First, whereas the conventional PPE industry is dominated by a small number of giant suppliers (CDC 2020), the pop-up PPE supply chain permitted entry of many small- to medium-sized suppliers. This diversity in suppliers was possible because of the low cost of producing certain PPE, which made quickly pivoting to PPE viable even for small-scale suppliers. For example, a single face shield can be assembled by hand, using materials that total $1.50 (UW Makerspace 2020). This simplicity made it possible for many suppliers to rapidly and temporarily enter the PPE industry during the surge in demand that began in March 2020.

Second, PPE produced by conventional suppliers is often purchased in large quantities and distributed by the federal government during emergencies (FEMA 2020). Major suppliers may also be subject to state-imposed export bans (Swanson et al. 2020). By contrast, suppliers in a pop-up supply chain typically sell directly to end users. This gives small organizations—who may otherwise be overlooked if distribution is centralized at the state or federal level—a better chance of acquiring PPE. Furthermore, the large number and geographic dispersion of suppliers in a pop-up supply chain enable organizations in need of PPE to potentially source from a local supplier, which can reduce both delivery times (through shorter shipping distances) and prices (through lower transportation costs or altruism).

As discussed previously, whereas the pop-up PPE supply chain helped to fill an unmet need for PPE, its ad hoc nature made procurement challenging. We view Shield-Net's role as supporting the operation of the pop-up PPE supply chain by matching suppliers with requesting organizations. Although our focus in this paper is on PPE, we briefly discuss other possible contexts where similar pop-up supply chains may arise in the Discussion section.

The remainder of the paper is organized as follows. In the Shield-Net Development section, we discuss the development and implementation of our matching platform, including data collection and the optimization model used to construct the matches. In the Evaluation section, we evaluate the impact that our platform had on helping organizations procure PPE. In the Discussion, we discuss the lessons learned during the operation of our platform, the limitations of our approach, and potential directions for future work.

Shield-Net Development

In this section, we provide more details on the development of Shield-Net and discuss how the system was implemented.

Problem Setting

In March 2020, UW Health, a regional health system in Wisconsin, first encountered difficulties with PPE procurement. To mitigate the shortages, administrators from UW Health approached the Director of the University of Wisconsin–Madison Grainger Engineering Design Innovation Laboratory (UW Makerspace) to ask if they could produce 1,000 face shields for UW Health workers. Members of the UW Makerspace collaborated with Midwest Prototyping, a local low-volume production facility, and Delve, a local design consulting firm, to quickly design, prototype, test, and produce a simple open-source face shield called the *Badger Shield*.

The Badger Shield received significant press attention both locally (Bhargaw 2020, Dahdah 2020, Kliese 2020, NBC 15 News 2020) and nationally (Ip 2020, Zastrow 2020). The media attention prompted United States Senator for the State of Wisconsin, Tammy Baldwin, to ask the UW Makerspace to help connect healthcare facilities in the state (and potentially beyond) to producers of face shields. Concurrently, the UW Makerspace began receiving requests for large quantities of Badger Shields from hospitals around the state and in areas hardest hit at the start of the pandemic (e.g., New York and California). At the same time, local suppliers expressed an interest in producing Badger Shields at a large scale. Initially, UW Makerspace staff supported the movement of Badger Shields by manually matching suppliers with healthcare facilities via email. However, a surge in interest on both the demand and supply side made manual matching prohibitively time-consuming and established the need for a system that could generate matches in a more efficient and impartial manner.

In response, we developed Shield-Net to serve as a matchmaker between suppliers and requesters of face shields. Our objective was not to act as a clearinghouse but simply to match potential buyers and sellers. We encouraged Shield-Net users to maintain their supplier-requester relationships after being matched and, if satisfied, to share supplier information with other organizations in need of face shields. Shield-Net development was conducted in three stages: (1) creation of online intake forms to collect data from suppliers and requesters (data collection), (2) development of an optimization model to conduct the matching (model), and (3) implementation of the matching system via a website (implementation).

Before proceeding, we note that the Badger Shield was available in two types: (1) fully assembled and (2) as a kit that required assembly. This distinction was made to provide requesting organizations with flexibility based on their budget and capacity for assembly.

Data Collection

We created two online forms to collect matching data: one for suppliers and one for requesters. We summarize the key components of each form here; please see Appendix B and Appendix C for complete copies of the requester and supplier forms, respectively. The supplier form focused on collecting information such as production rate (for each type), facility location, acceptable payment methods, and contact information for further verification. The requester form collected data on the number of shields needed (of which type), self-reported urgency, facility location/type/size, payment type, and contact information. Self-reported urgency was ranked on a scale from 1 to 3, and sample rankings were provided for context. For example, a hospital treating COVID-19 patients was classified as level 3, whereas a grocery store was level 1. We set a lower limit for shield requests at 100 based on conversations with suppliers about cost-effectiveness (many medical facilities treat face shields as disposable). We provide details on how this information was used for matching in the next section.

Model

In this section, we describe the overall matching framework and provide a brief description of our optimization model. The purpose of the optimization model is to create supplier-requester matches that account for request size, urgency, supplier production capacity, location, and product type.

Let I denote the set of suppliers. Each supplier has committed to produce a fixed quantity of face shields each day, denoted by s_i. Let J denote the set of facilities requesting face shields ("requester"). Each requester submits a one-time request for face shields, denoted d_j. We refer to (i, j) as a *match* if the model recommends a nonzero allocation of face shields from supplier i to requester j. Let a_{ij} be a binary parameter that is equal to 1 if supplier i and requester j have compatible product types, and 0 otherwise. The parameter a_{ij} is used to encode a priori information regarding the suitability of the match (i, j); specifically, we use a_{ij} to encode whether the face shield type (fully assembled or requires assembly) is compatible between supplier i and requester j. Let $p_j \in \{1, 2, 3\}$ be a weight parameter that reflects the self-reported priority of requester j. Let c_{ij} be the unit cost of shipping from supplier i to requester j (e.g., distance, shipping time); in our implementation, we set c_{ij} to be the Euclidean distance between the centroids of the states where supplier i and requester j are located, measured in kilometers.

Let x_{ij} be a continuous variable that represents the number of units allocated from supplier i to requester j. Let t_j represent the demand shortfall of requester j. Let $\alpha > 0$ be a penalty constant parameter that captures the relative importance of the shipping cost.

Next, we define the constraints and objective of our optimization model. We first impose the following constraints on the match quantities:

$$\sum_{j \in J} x_{ij} \le s_i, \quad i \in I, \tag{1a}$$

$$\sum_{i \in I} x_{ij} \le d_j, \quad j \in J, \tag{1b}$$

$$x_{ij} \le d_j a_{ij}, \quad i \in I,\ j \in J. \tag{1c}$$

The first two constraints ensure that the total match quantity for each supplier does not exceed their capacity and that a requester is not matched for more face shields than they requested. The third constraint ensures that requesters are only matched to suppliers who produce a compatible product type. This constraint is necessary because many suppliers can produce multiple product types (i.e., both preassembled and unassembled face shields), which precludes decoupling the matching process by product type. Next, we include the constraints

$$t_j \ge d_j - \sum_{i \in I} x_{ij}, \quad j \in J, \tag{2a}$$

$$t_j \ge 0, \quad j \in J, \tag{2b}$$

which ensure that t_j captures the demand shortfall of requester j at an optimal solution to the model.

We now define the objective function, which consists of two terms. The first term represents the total demand shortfall over all requesters, weighted by urgency: $\sum_{j \in J} p_j t_j$. Including the weights p_j prioritizes requesters that reported an urgent need for face shields. The second term is the total match distance, weighted by the penalty constant α: $\alpha \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij}$. The purpose of this term is to reduce transportation costs by encouraging the model to match suppliers and requesters that were geographically close. In our implementation, we set $\alpha = 10^{-6}$, which we observed to be effective at producing same-state matches. Combining our objective with the constraints defined above yields the following optimization problem:

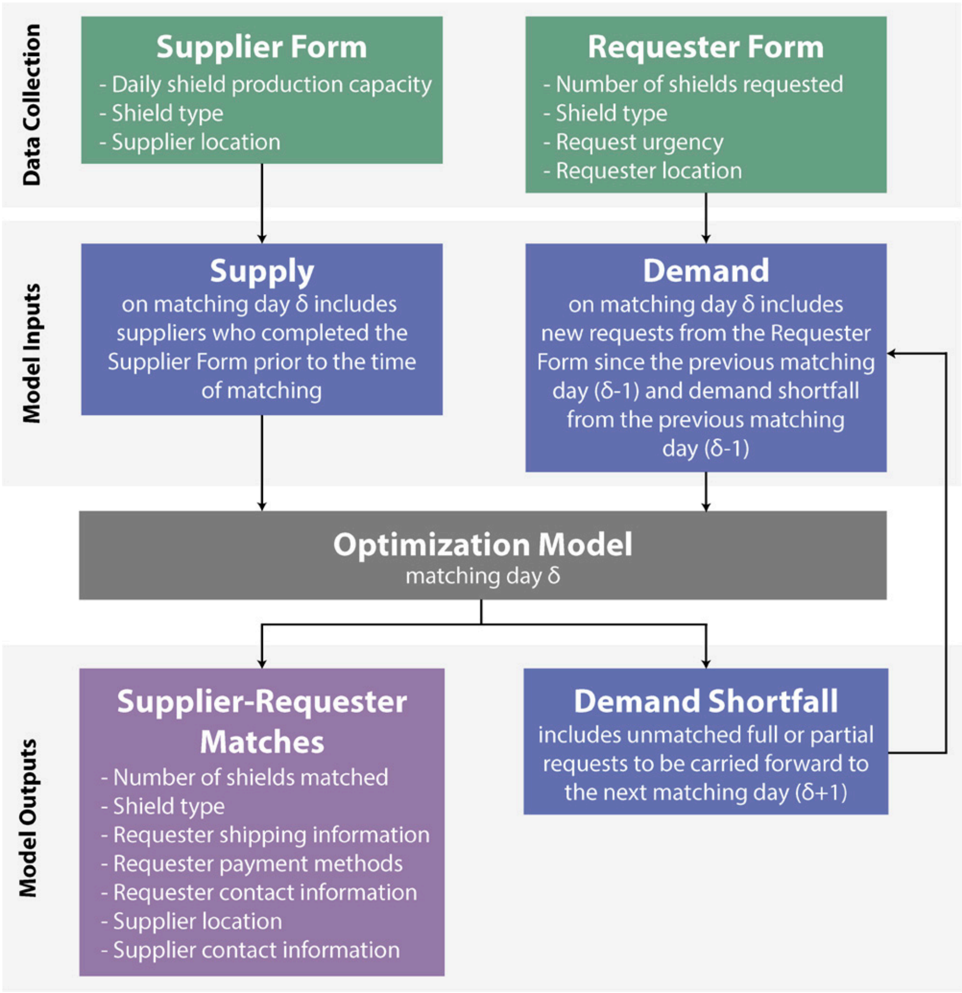
$$\begin{aligned} \underset{\mathbf{x},\mathbf{t}}{\text{minimize}} \quad & \sum_{j \in J} p_j t_j + \alpha \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} \\ \text{subject to} \quad & \text{Equation (1) through Equation (2)}, \\ & x_{ij} \ge 0, \quad i \in I, j \in J, \end{aligned}$$

At an optimal solution $(\mathbf{x}^*, \mathbf{t}^*)$, the nonzero entries of $\mathbf{x}^*$ represent the pair-wise matches produced by the model, and the variable $\mathbf{t}^*$ represents the demand shortfall that needs to be carried over to the next round of matching.

Implementation

Figure 1 displays a process flow diagram of the Shield-Net system. We implemented the entire system, including the optimization model, in the Python programming language, using Gurobi as the solver (Gurobi Optimization 2021). Our main script imported supplier and request data from the online questionnaires and parameterized the optimization model accordingly. Suppliers typically submit a single form when production comes online (follow-up submissions can be used to adjust production rates, lead times, etc.), whereas requests are made on a continuous basis by organizations in need. On the first day of

Figure 1. (Color online) Shield-Net System Comprised Four Principle Components: (1) Data Collection, (2) Model Inputs, (3) Optimization Model, and (4) Model Outputs



Note. The process by which the optimization model handled the inputs, particularly new demand and demand shortfall, and outputs is also shown.

matching, we used only these intake forms to parameterize the model. For subsequent days, we also account for any demand shortfall to be carried forward from a previous matching day (shown by the feedback loop in the diagram). We ran the script and solved the corresponding optimization model twice per week. The output of the script was a set of automatically generated emails containing the match information (supplier, requester, match quantity, and product type), which was then sent jointly to the supplier and requester. The information in each email was automatically populated based on the optimal solution produced by the model.

In general, requesters were removed from our system once they were matched, and suppliers were kept in the system unless they requested to be removed. This is because requesters generally had a one-time need for face shields, whereas most suppliers had the capacity to continuously produce face shields and could be used to satisfy demand in future matches. We did not instruct suppliers to start or stop production based on the matches or requester data in our system because they may have also had buyers outside of our platform.

The system is accessible through our website: http://shield-net.org. During operation, the landing page included links to both questionnaires described in the Data Collection section, a high-level description of the system, and links to details of the Badger Shield design and the supplier database (see Appendix A for a screenshot of the landing page). The website was also linked directly from the UW Makerspace website to encourage users to submit requests through the Shield-Net system rather than via email. To supplement every match, we provided postmatch support, including directly sharing the database of all suppliers in the Shield-Net system, collecting their feedback on the system, and, if needed, offering to rematch them.

Evaluation

In this section, we first describe the data collection process for obtaining feedback on supplier-requester matches, including whether the match was "successful" (i.e., resulted in a transaction). We then share the results of the Shield-Net implementation, including metrics on the utilization of the platform and match success rate.

Data Collection

The Shield-Net platform was not designed to handle transactions between suppliers and requesters and, as a result, did not directly collect data on which matches were successful. To supplement the system, we manually followed up with suppliers and requesters to identify successful matches. We sent suppliers their match history and asked them to confirm which matches resulted in a transaction. For successful matches, suppliers were encouraged to provide us the order quantity, shipment date, shipment tracking number, and the price per unit.

For requesters, a unique identifier was automatically generated for each of their matches. We emailed this ID to requesters along with a link to an online form. The form asked if the match associated to the ID number was successful. Depending on their response to this question, requesters were directed to two different sets of remaining questions. Requesters who answered that their match was successful were subsequently asked if their face shields had been delivered and if they could provide the shipment's tracking number. Those who responded indicating an unsuccessful match were asked what factors contributed to their match being unsuccessful (e.g., price, lead time, quality) and if they would like to be rematched. Both groups were also given the opportunity to share feedback on their experience with the Shield-Net platform.

Utilization

Between March 23, 2020, and September 11, 2020, our platform was visited by 11,027 unique users, accumulating 12,432 total sessions of active website engagement. Interestingly, 64% of the site's visits came from referrals, primarily from *averagesocialite.com*, where resources for healthcare workers were being promoted. Another 34% of site visits were attributed to users directly entering the site's URL into their browser. The remaining 2% of visits originated from organic searches and social media. Once on the Shield-Net website, visitors were able to submit requests for face shields or upload their organization's information to the supplier database.

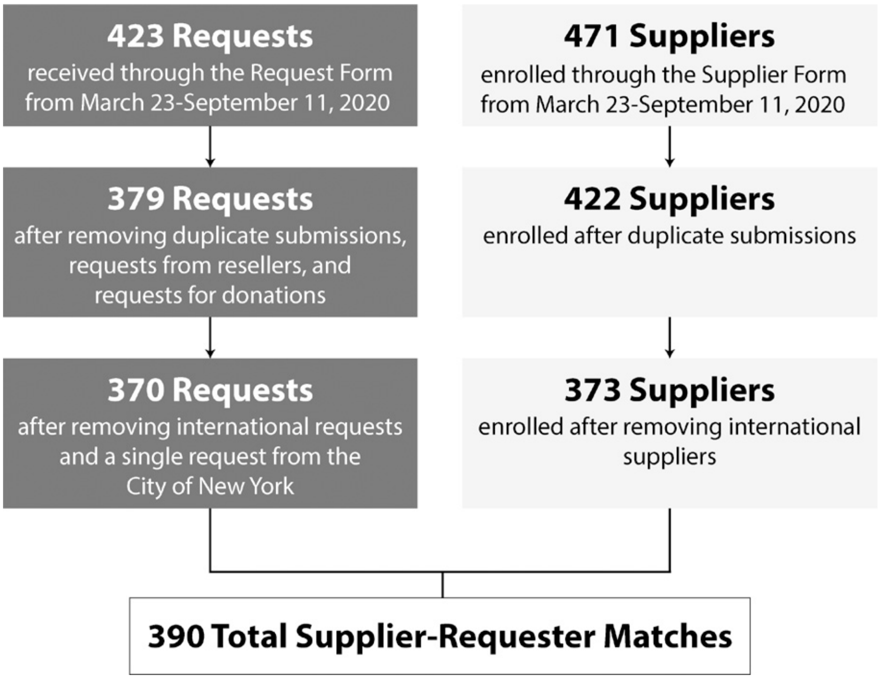
During its operation, Shield-Net received 423 requests for face shields. Of these, 44 were removed from the analysis because they were found to be duplicate submissions, requests from resellers, or requests for donations. We redirected requesters seeking donations to the supplier database and other platforms supporting donation requests. After culling, there were 379 valid requests that summed to approximately 400,000 face shields. Eight of these requests originated outside of the United States, in Australia, Canada, Chile, and England. These international supplier-requester matches were handled manually and thus also removed from the analysis.

Additionally, on March 24, 2020, a public servant representing the City of New York and procuring face shields on behalf of NYC Health+ Hospitals requested 5 million shields through Shield-Net. The size of this request was 50 times greater than the next largest request. After several rounds of matching, it became clear that this request was beyond the scope of our platform, despite suppliers' willingness to engage. We determined that the requester did not have the bandwidth to actively participate in the matching service at that time and removed them from the matching system.

In total, 362 unique organizations from 43 states and Puerto Rico constituted the remaining 370 requests, totaling 393,931 face shields. Figure 2 displays an inclusion diagram. The highest proportion of requests (28%) came from organizations in Wisconsin, followed by California, New York, and Texas. The average request size was approximately 1,065 face shields with the largest being 100,000 shields. The number of requests and the total number of shields requested by state are shown in Figure 3, (a) and (b). On average, the organizations requesting face shields employed 1,476 workers. Requests were nearly evenly split by product type: 170 organizations preferring kits versus 200 organizations requesting fully assembled shields.

Over the same time period, 471 suppliers from around the world, including countries such as Canada, Nigeria, India, Germany, and Cambodia, joined the Shield-Net database. Similar to international requests, international suppliers (n = 49) were not enrolled in the matching service because matches were handled manually, although these suppliers were still listed in the public database. An additional 49 suppliers were removed for duplicate submissions. The remaining 373 suppliers came from 40 states with an aggregate daily capacity to produce approximately 6 million face shields. The number of suppliers and the total production capacity as distributed by state at the end of the implementation period are shown in Figure 3, (c) and (d). Again, the highest proportion of suppliers came from Wisconsin (13%), with California, New

Figure 2. Inclusion Diagram for Requests and Suppliers for Who Was Ultimately Included in the Matchmaking



Note. There are more matches than requests because demand shortfall that was carried over to the next matching day was counted as a separate match.

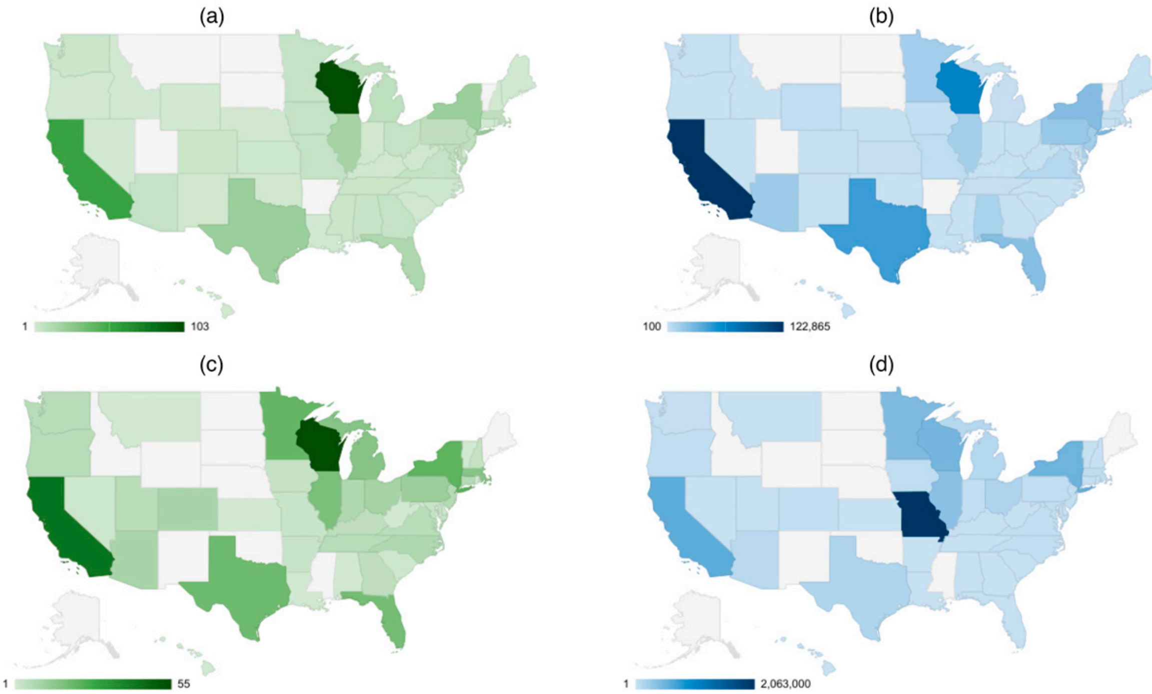
York, Texas, and Minnesota close behind. Despite a larger number of suppliers in other states, the greatest manufacturing capacity was found in Missouri; one supplier in the state indicated it had capacity to produce 2 million shields per day. However, this supplier did not join the Shield-Net database until April 29, after the initial surge of implementation. As a result, the supplier was not used directly in the matching service. Last, just 36 suppliers specified that they were only able to produce face shield kits. The majority of suppliers (n = 213) were offering only fully assembled face shields, whereas 124 marketed both options.

Match Success Rate

We produced 390 supplier-requester matches between March 25, 2020, and September 16, 2020. We received a response from either a supplier or requester indicating whether their match was successful for 65% of all matches (n = 255). We refer to the remaining 35% of matches as "unclassified." A total of 69 matches were found to be successful, representing delivery of 50,925 face shields. Figure 4 shows the temporal distribution of Shield-Net matches, categorized by those that resulted in a successful match, an unsuccessful match, or an unclassified match. Several Shield-Net users who provided the status of their match success also shared qualitative feedback on the platform. One requester wrote, "They arrived 2 days after we ordered. [We] are very pleased with the whole process." Another shared the face shields they received and supplier information with others, saying, "This was great—I shared part of my order with three other providers who were in need and passed of [sic] the supplier info to some people as well." These testimonies represent the ideal outcome for the Shield-Net platform: a requesting organization, satisfied with the match, maintains its relationship with the supplier and thus no longer needs the platform. Eight requesters independently returned to the platform at a later date to request additional shields.

Of those who responded reporting an unsuccessful match, 52% indicated they fulfilled their face shield orders elsewhere, although some indicated they had procured face shields using a manufacturer they identified via Shield-Net's publicly available database, or they saved their match information for possible future use. This strategy is exemplified in the feedback provided by one requester from an emergency management division of a midsized community in Arizona: "[Shield-Net] connected me with a very good vendor—however, prior to contact from them, my government entity was able to procure face shields from another source. We have retained his information in case we have future needs." We hypothesize that many requesters treated Shield-Net as a "safety net" (the platform's naming inspiration) and that they preferred formal procurement channels that were more

Figure 3. (Color online) Number of Requests and Production Capacity as of September 2020 by State



Notes. (a) Number of requests. (b) Number of shields requested. (c) Number of suppliers. (d) Production capacity (shields per day).

familiar and regulated. Therefore, although a majority of matches did not result in an order being placed by the requester (possibly because they successfully procured face shields elsewhere), Shield-Net still provided value to requesters by serving as a backup option.

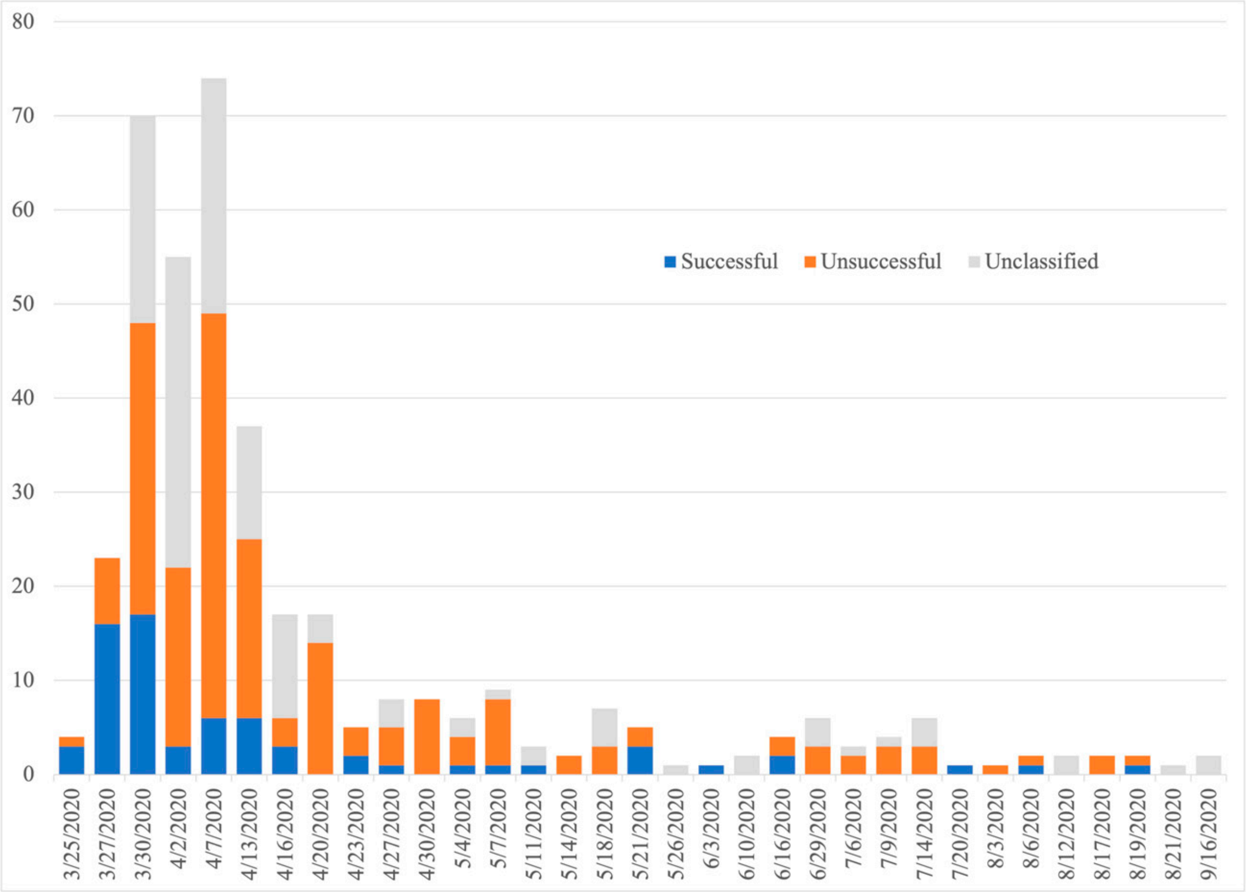
Given that Shield-Net was designed to be a temporary and informal alternative for procuring face shields, we view the overall match success rate of 27%, calculated by dividing the number of successful matches by the total number of matches for which we received information on their outcome, as a sign of the platform's overall success. More conservatively, the match rate can be calculated using the total number of matches, by which we obtain a match success rate of 18%. We note that it is important to interpret Shield-Net's unsuccessful match rate (73% low estimate, 82% high estimate) in the context of other online matching platforms. For example, the unsuccessful match rate for Tinder (an online dating platform) was found to be 90% for women and 99.4% for men (Tyson et al. 2016). Similarly, the unsuccessful match rate for holiday rental platforms (like AirBnB) ranges from 85% to 91% (Fradkin 2017, Li and Netessine 2020), and the unsuccessful match rate for an employment matching platform was found to be 65% (Horton 2019). The performance of Shield-Net was similar to the performance of these platforms, so it is difficult to determine whether the high unsuccessful match rate is characteristic of its specific setting, matching platforms more generally, or the nature of the matches themselves.

To further analyze the features that influenced match success, we fit a logistic regression model to estimate which match characteristics were positively and negatively associated with a match's success. Our model included the following eight features: supplier production rate, request amount, request type, request urgency, difference in request amount versus match amount, number of employees (requester), number of patient beds (requester), requester organization type (hospital with more than 300 beds, hospital with fewer than 300 beds, nursing home, other care facility, other). We fit the model on all data and found that local proximity, defined as both parties being in the same state, was the only significant feature ($p < 0.001$) for predicting match success, whereas all other features were insignificant at the $p = 0.1$ level. Specifically, we found that a local match increased the odds of a successful match by 250% (odds ratio = 3.55; 95% confidence interval (CI), 1.89–6.64).

Supplier-Requester Proximity

As noted earlier, we identified one dominant feature that influenced whether a match was successful: the proximity of the supplier and requester. Based on this finding, we conducted a retrospective experiment to characterize how α (the objective weight for match proximity) affects the proportion of local (i.e., intrastate) matches. Our implementation used $\alpha = 10^{-6}$, which resulted in 48% of the matches being local. For our retrospective analysis, we reran the matchmaking

Figure 4. (Color online) Number of Face Shield Requests by Match Success Category for Each Matching Day During the Implementation Period



for each day that Shield-Net was active using seven different α values: $\alpha = 10^{-x}$ for $x \in \{1, 2, \ldots, 7\}$. For each instance, we computed the proportion of intrastate matches and the total number of shields matched. The results from our retrospective experiments do not align exactly with reality (i.e., the experimental results for $\alpha = 10^{-6}$ are not exactly the same as the real implementation results) because of human intervention in the matchmaking process. For example, manual matches were made when suppliers reached out with excess supply or wanted to donate supply to local organizations in need. Figure 5 displays the intrastate match proportion and the total number of matches for different α values with the results from our implementation.

We conjecture that two factors contributed to the success of intrastate matches. First, the shorter distances represented by these matches may have resulted in lower shipping costs or time. Second, intrastate matches may have brought a sense of trustworthiness to an unfamiliar process and improved the supplier-requester relationship. This success highlights the potential benefits of localized, pop-up supply chains during humanitarian emergencies and their advantages over traditional global supply chains.

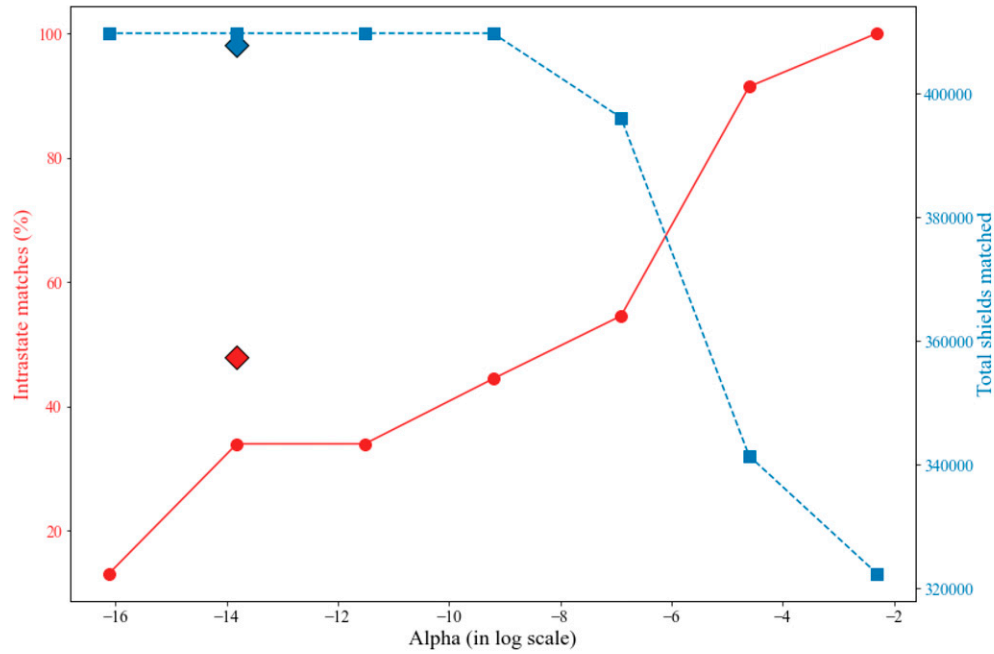
Discussion

In this section, we discuss some of the factors that contributed to Shield-Net's viability, in addition to potential sources of inefficiency that may have negatively affected the match success rate.

Factors Contributing to Shield-Net's Viability

Automation. The Shield-Net platform initially relied on manual matchmaking and would have continued to make manual matches in the absence of our optimization model. The first (and only, besides few special cases mentioned previously) manual matches were sent on the evening of March 24, 2020, one day after the platform launched. By this time, 34 requests had already been made from organizations in 13 states, totaling 5,030,250 face shields (recall the City of New York placed an order for 5 million shields and the request had not yet been excluded from matchmaking). Similarly, nine manufacturers from six states had

Figure 5. (Color online) Comparison of the Intrastate Match Proportion (Circles) and Total Number of Shields Matched (Squares) for Different Values of α



Note. Results from Shield-Net's real-world implementation are displayed as diamonds.

enrolled in the supplier database with a collective daily capacity to produce over 30,000 face shields. As a result, in the first 24 hours of the platform, there were already approximately 300 possible matches for UW Makerspace staff to consider.

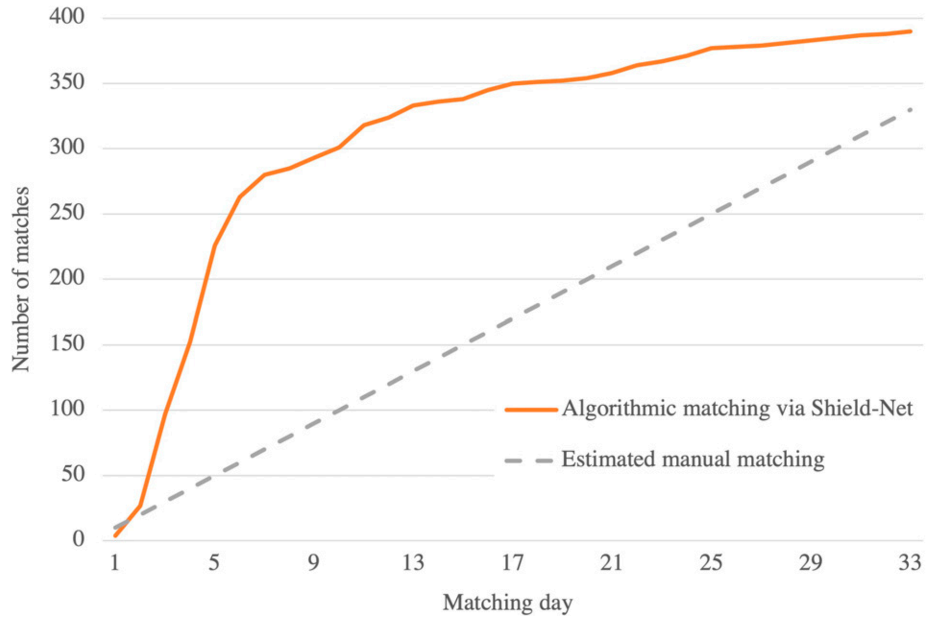
The process to manually curate a single match involved six steps: (1) review the request to understand the request size, request priority level, the location of the requester, and the requester's preferred product type; (2) review the supplier database to determine which suppliers offered the type of face shield requested and whose daily production capacity was sufficient to fulfill the request (if possible); (3) evaluate the proximity of the requester and remaining suppliers; (4) choose a supplier to fulfill a full or partial request based on the matchmaker's best judgment; (5) connect the supplier and requester via email with match information; and (6) log match information, including whether any demand from the request needed to be carried forward for future matchmaking. Moreover, these decisions had to be made within context of the other matches to ensure that a variety of suppliers were used and a lower-priority request was not matched before a higher-priority request.

Following the approach of Bala et al. (2021) and based on the authors' experience with manual matching from the first day of implementation, we estimate that one manual match would require one hour of time from a volunteer, on average. This is likely a conservative estimate because the first three manual matches took five total hours to complete and the manual matchmaking process would have become increasingly difficult as the databases of requests and suppliers grew (Bala et al. (2021) estimated each match took 93 minutes).

Figure 6 visualizes the cumulative number of matches for a single manual matchmaker who worked 10 hours per day (i.e., 10 matches per day) versus the actual number of matches made by the platform. The largest number of matches made on a single day was 74, which would have required roughly 74 hours of human matchmaking capacity. Automated matching was a key contributor the success of Shield-Net in its role to support the pop-up PPE supply chain, and any tools developed around future pop-up supply chains, especially at scales commensurate with or greater than Shield-Net, will likely also benefit from the efficiency gained in implementing an automated matchmaking platform.

Product Suitability. A major reason why Shield-Net was viable was the simple, low-cost design of the product, which created a welcoming environment for new suppliers to begin PPE production. In the case of the Badger Shield developed by the UW Makerspace, Midwest Prototyping, and Delve, the design consisted of only three components (polyester film, an elastic band, and polyurethane foam) and could be

Figure 6. (Color online) Cumulative Number of Matches for a Single Manual Matchmaker Who Worked 10 Hours per Day (i.e., 10 Matches per Day) Compared with the Actual Number of Matches Made by the Shield-Net Platform



constructed by hand with a pair of scissors and a stapler or in bulk with a rotary die cutting press. Furthermore, the design was made publicly available and usable by anyone without payment or permission. Because more-complex products (e.g., ventilators) are less likely to be manufactured by nontraditional suppliers, they are less likely to lead to the formation of a pop-up supply chain. Other products in high demand during the COVID-19 pandemic, such as N95 respirators, may also have been subject to more-stringent regulations and met with greater skepticism and resistance by requesting organizations. The simplicity of face shields, by contrast, made internal and informal quality-inspection efforts possible, giving end users greater confidence in wearing the product.

Supplier Benefits. Although the primary aim of Shield-Net was to enable organizations to quickly source face shields, the platform also benefited suppliers by allowing them to continue operating during widespread economic shutdown of nonessential business. Transitioning to PPE production even allowed one supplier to hire additional employees: "Our transition to PPE production also allowed us to stay busy during COVID-19 shutdowns, keeping our regular staff of 40 employees working while also allowing us to hire 8 additional employees to help with the PPE business." The clear benefit to suppliers helped to secure their participation on our platform, which was vital for its operation.

Potential Sources of Inefficiency

We now discuss three issues we did not explicitly account for in our model, which may have negatively affected the match success rate: uncertainty in product quality, minimum order quantities, and price variability.

Quality. Uncertainty in product quality and a lack of U.S. Food and Drug Administration (FDA) certification may have led requesters to be reluctant to place an order with their matched supplier. Whereas PPE produced by traditional suppliers is typically certified by the federal government (CDC 2020), the time-sensitive nature of procuring PPE coupled with the cost required to pursue certifications made it difficult for suppliers in the Shield-Net system to receive similar approvals. As Shield-Net grew in popularity, the reliability of the suppliers and product quality within the system became increasingly uncertain.

During the initial weeks of its operation, suppliers participating in Shield-Net were only producing face shields using the suggested Badger Shield design. However, as the platform's reach expanded, suppliers of alternative face shields began joining Shield-Net. In some cases, requesting organizations were expecting the Badger Shield design and were surprised to learn that their matched supplier was actually using a three-dimensional (3D)-printed or bandless design. For example, one hospital noted, " … I will also mention that our staff prefer [the Badger Shield] over some ones we got from our distributors." After learning this, we asked suppliers to submit the technical specifications for their design accompanied by a photo so that we could conduct informal quality inspections. The products were then reviewed manually, and the set of candidate suppliers was refined.

We believe Shield-Net would have benefited if suppliers had the option to quickly obtain an intermediate-level PPE certification (e.g., perhaps by regional bodies sanctioned by the FDA), which would have signaled a minimum guaranteed level of quality to requesters. Such certifications would have been helpful for Shield-Net and the face shield market in general during the early months of the pandemic by reducing quality uncertainty and improving requesters' confidence in suppliers.

Minimum Order Quantity. On the supplier side, anecdotal evidence suggests that the number of face shields requested may have affected suppliers' willingness to fulfill an order. Based on conversations with suppliers, we initially imposed a minimum order quantity of 100 shields. However, as suppliers with much larger production capacity joined, we learned that even 100 shields were below the minimum order quantity that some suppliers were willing to accept. For example, one supplier wrote, "We're having plenty of people reach out with orders too small for us to handle efficiently." This suggests that the match success rate may have been negatively impacted by suppliers declining to fulfill small orders and that accounting for minimum order size in the model may have improved the match success rate.

Pricing. Our platform did not consider price when creating matches and instead allowed suppliers and requesters to negotiate price once they were matched. This was potentially a source of inefficiency in our platform because our model did not account for whether a requester would be willing to pay the price offered by their matched supplier. We encouraged suppliers to sell the shields "at cost" if possible to ensure that prices were not prohibitive for the majority of requesters. Based on the data later collected from suppliers, we found price to be highly variable across suppliers, with unit prices ranging from $1.00 to $7.00. Soliciting suppliers' prices and requesters' willingness to pay and incorporating this information into the model may have further improved match outcomes.

Conclusion

In this paper, we discussed the implementation of an online matching platform, Shield-Net, that we deployed in March 2020 to improve coordination between face shield suppliers and requesters. The platform was based on an optimization model that produced supplier-requester pairs, taking into account various supplier and requester characteristics. During the operating period, Shield-Net produced 390 matches, resulting in the shipment of more than 50,000 face shields to 68 unique requesting organizations. In addition to helping the requesters who were in need of face shields, Shield-Net also benefited suppliers by allowing them to continue operating during widespread economic shutdowns.

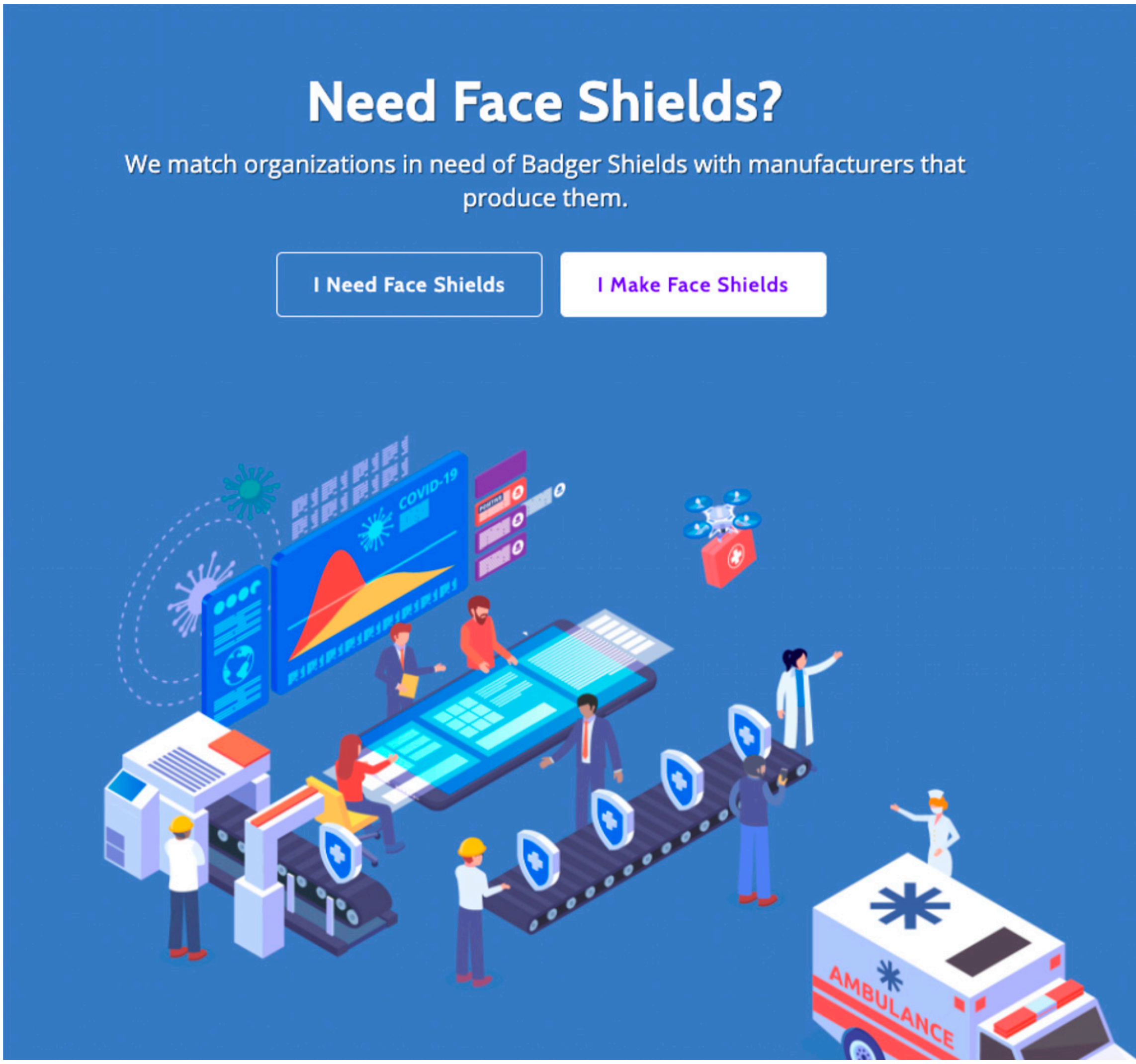
Although Shield-Net focused on the distribution of PPE, similar platforms may be useful in matching supply with demand for critical supplies during other emergencies—for example, matching generators to homes without power after severe storms or crowdsourcing volunteers to aid with disaster cleanup and recovery in affected areas. Our work carries lessons for similar matching platforms that might be deployed in the future. First, our analysis of match outcomes revealed that the proximity of the supplier and requester was highly predictive of match success, which may generalize to other contexts as well. Furthermore, feedback from participants on the platform suggests that future matching platforms would stand to benefit from explicitly addressing quality uncertainty, minimum order quantities for suppliers, and price variability within the matching algorithm.

Last, with respect to future research, it may be fruitful to investigate the behavior of pop-up supply chains within a more general modeling framework. To the best of our knowledge, the concept of a pop-up supply chain has not appeared elsewhere in the supply chain management literature; previous work on humanitarian logistics has typically focused on a central decision maker responsible for the allocation of resources (see Altay and Green (2006) and Sabbaghtorkan et al. (2020) for reviews). By contrast, our setting involves a set of nontraditional suppliers rapidly responding to a demand spike within a preexisting market, the analysis of which may lead to interesting and novel findings.

Acknowledgments

The authors thank those at the University of Wisconsin–Madison Grainger Engineering Design Innovation Laboratory who worked on open-source PPE efforts for being receptive to the implementation of Shield-Net amid the chaos of responding to the COVID-19 pandemic. The authors also acknowledge the support of Yuan Ma and Benjamin Viggiano in collecting follow-up data from participating hospitals and suppliers and conducting preliminary data analyses. Last, the authors extend their deepest gratitude to the suppliers who eagerly participated in an unfamiliar supply chain system and organizations who trusted Shield-Net to support their procurement of face shields.

Appendix A. (Color online) Shield-Net.org Landing Page



Appendix B. (Color online) Requester Form

2/4/2021 COVID-19 Face Shield Request

COVID-19 Face Shield Request

This form is to be used to request face shields as shown on our website. https://making.engr.wisc.edu/shield/

How it works:
- Through publication of the University of Wisconsin's open source face shield design, a community of manufacturers of varying sizes has formed, many of which have adapted part of their production line to make these shields.

- Filling out the form below will enter your organization into an early version of an online matching system that co-ordinates communication between healthcare organizations in need of face shields and manufacturers that are producing them.

- Once you are matched with a manufacturer, you will receive an email with their contact information and further instructions.

- Please note that due to possible supply constraints, healthcare facilities may be matched with multiple manufacturers over multiple rounds. This system is for co-ordinating matches between healthcare facilities and face shield manufacturers only; we do not handle billing or payment.

* Required

1. Organization Name *

____

2. Facility Type *

Mark only one oval.

- ◯ Hospital (greater than 300 beds)
- ◯ Hospital (less than 300 beds)
- ◯ Nursing Home
- ◯ Other Care Facility
- ◯ Government Entity
- ◯ Other: _______________

3. Number of Beds You Service *

____

4. Number of healthcare workers / medical staff *

____

https://docs.google.com/forms/d/1_05Oa-LQvo5Abs8awdo-Cd_fstUC2_aa8L0V0Sx-yDo/edit

2/4/2021 COVID-19 Face Shield Request

Request Details

5. Enter the number of Face Shields needed. Please resubmit this form for subsequent orders. *

6. Rank your order urgency. 3-high urgency (e.g., hospital in NYC), 2-medium urgency (e.g., other healthcare facilities dealing with COVID-19 patients), 1-low urgency (e.g., shields needed to continue business operations) *

Mark only one oval.

	1	2	3	
Lowest Urgency	○	○	○	Highest Urgency

7. In what form would you like to receive the face shields? (Prices shown are estimates. Actual price will be set once connected to a manufacturer based on their materials.) *

Mark only one oval.

- ○ Fully assembled
- ○ Kit form

8. What form of payment are you able to use? Select all that apply. *

Check all that apply.

- ☐ Credit/Debit Card (over the phone)
- ☐ PayPal
- ☐ Purchase Order

Other: ☐

Shipping Information

9. Name

10. Street Address *

11. City *

https://docs.google.com/forms/d/1_05Oa-LQvo5Abs8awdo-Cd_fstUC2_aa8L0V0Sx-yDo/edit

2/4/2021 COVID-19 Face Shield Request

12. State *

Mark only one oval.

- Alabama
- Alaska
- Arizona
- Arkansas
- California
- Colorado
- Connecticut
- Delaware
- Florida
- Georgia
- Hawaii
- Idaho
- Illinois
- Indiana
- Iowa
- Kansas
- Kentucky
- Louisiana
- Maine
- Maryland
- Massachusetts
- Michigan
- Minnesota
- Mississippi
- Missouri
- Montana
- Nebraska
- Nevada
- New Hampshire
- New Jersey
- New Mexico
- New York
- North Carolina
- North Dakota
- Ohio

https://docs.google.com/forms/d/1_05Oa-LQvo5Abs8awdo-Cd_fstUC2_aa8L0V0Sx-yDo/edit

2/4/2021 COVID-19 Face Shield Request

- Oklahoma
- Oregon
- Pennsylvania
- Rhode Island
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Vermot
- Virginia
- Washington
- West Virginia
- Wisconsin
- Wyoming
- Puerto Rico
- Outside of the USA

13. Zip Code *

14. Shipping Details (e.g. c/o, internal routing info, etc.)

15. Do you have a shipping account with UPS, FedEx, etc.? Please provide the information below.

16. Best Single Point of Contact: First Name *

https://docs.google.com/forms/d/1_05Oa-LQvo5Abs8awdo-Cd_fstUC2_aa8L0V0Sx-yDo/edit

2/4/2021 COVID-19 Face Shield Request

17. Best Single Point of Contact: Last Name *

18. Best Single Point of Contact: Email *

19. Best Single Point of Contact: Phone (###-###-####) *

Appendix C. (Color online) Supplier Form

2/4/2021 COVID-19 Face Shield Manufacturer Follow-Up

COVID-19 Face Shield Manufacturer Follow-Up

Responses to this form will be used to connect you to medical facilities in need of face shields based on location, quantity available, etc.

* Required

1. Organization Name *

____

We will be reaching out to get updates on production, lead times, etc. over the ensuing weeks. Please provide information below for the best single point of contact who we can rely on for this information.

2. Best Single Point of Contact: First Name *

____

3. Best Single Point of Contact: Last Name *

____

4. Best Single Point of Contact: Email *

____

5. Best Single Point of Contact: Phone *

____

Face Shield Production

These questions will be used to match you to medical facilities in need.

6. What quantity of face shields do you currently have available to be shipped? *

____

7. How many face shields can you ship each day? If anything changes (e.g. your facility can ship more or less masks per day), please resubmit the form with the updated information. *

8. In what form/state (e.g. fully assembled or kit) will you ship the face shields to medical facilities? If you are not the end point in the supply chain, please do not continue filling out this form. *

Mark only one oval.

- Fully assembled
- Kit form
- Either/Both

9. Facility Street Address *

10. City *

2/4/2021 COVID-19 Face Shield Manufacturer Follow-Up

11. State *

Mark only one oval.

- Alabama
- Alaska
- Arizona
- Arkansas
- California
- Colorado
- Connecticut
- Delaware
- Florida
- Georgia
- Hawaii
- Idaho
- Illinois
- Indiana
- Iowa
- Kansas
- Kentucky
- Louisiana
- Maine
- Maryland
- Massachusetts
- Michigan
- Minnesota
- Mississippi
- Missouri
- Montana
- Nebraska
- Nevada
- New Hampshire
- New Jersey
- New Mexico
- New York
- North Carolina
- North Dakota
- Ohio

https://docs.google.com/forms/d/1LcydkWJmW2Inpx1ilv_DThTDZdF_gdzU9LfwXiiafvQ/edit

2/4/2021 COVID-19 Face Shield Manufacturer Follow-Up

- Oklahoma
- Oregon
- Pennsylvania
- Rhode Island
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Vermot
- Virginia
- Washington
- West Virginia
- Option 53
- Wisconsin
- Wyoming
- Puerto Rico
- Outside of the USA

12. Zip Code *

____

13. Can you ship anywhere in the US or Canada? *

Mark only one oval.

- Yes
- No
- Other: _______________

2/4/2021 COVID-19 Face Shield Manufacturer Follow-Up

14. What forms of payment will you accept? *

Check all that apply.

- [ ] Credit/Debit Card
- [ ] PayPal
- [ ] Purchase Order

Other: [ ] ____________________

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Verification Letter

Lennon Rodgers, Director, Grainger Engineering Design Innovation Labs, College of Engineering, University of Wisconsin, Madison, WI writes:

"In March of 2020, the University of Wisconsin Grainger Engineering Design Innovation Laboratory (UW Makerspace) was approached by UW Health with a request to produce 1,000 face shields. In response, we partnered with Delve, an innovation and product design consulting firm, and Midwest Prototyping, a midsize advanced prototyping facility, to produce the Badger Shield. The Badger Shield is a simple open-source face shield design that is highly manufacturable and scalable and was developed in response to shortages of personal protective equipment during the COVID-19 pandemic."

"After the Badger Shield design was released on our website (making.engr.wisc.edu/shield) and Midwest Prototyping met UW Health's urgent need, the work received significant and far-reaching media attention. Before long, healthcare organizations and manufacturers from around the country and world started requesting and producing the Badger Shield. This sudden spotlight on the UW Makerspace and the demonstrable evidence of both supply and demand led to an unexpected request from Tammy Baldwin, U.S. Senator for the State of Wisconsin. She asked that the UW Makerspace team serve as a liaison between organizations needing face shields and manufacturers producing them. Responding to Senator Baldwin's request, Rebecca Alcock, one of the UW Makerspace's graduate assistants at the time, began making manufacturer-requester connections manually. She soon realized that the project was growing too quickly and that manual matchmaking was not sustainable. Rebecca proposed an automated matchmaking platform to ensure the matches were made in a fair and timely manner."

"At this time, Justin Boutilier and Auyon Siddiq joined the team to design the platform, called Shield-Net, and integrate it into the UW Makerspace's ongoing COVID-19 projects. Before Shield-Net, organizations visiting our website in search of face shields were directed to a growing database of manufacturers. After launch, they were sent to the Shield-Net website (shield-net.org), where they were able to request shields, receive a curated match to a manufacturer, and review or usee the manufacturer database."

"Overall, Shield-Net was instrumental in increasing the reach and supporting the distribution of the Badger Shield, ultimately multiplying the impact of UW Makerspace's COVID-19 response. I also confirm that the publication's representation of the creation, implementation, and resulting impact of Shield-Net presented in "Shield-Net: Matching Supply With Demand for Face Shields During the COVID-19 Pandemic" by Rebecca Alcock, Justin Boutilier, and Auyon Siddiq, is accurate."

Rebecca Alcock is a PhD student in the Analytics for Human Development Laboratory at the University of Wisconsin–Madison (UW-Madison) in the Department of Industrial and Systems Engineering. She obtained her BS and MS degrees in biomedical engineering from UW-Madison. Her research mission is to combine her current training in optimization and machine learning with her background in product design to address pressing global health and planetary health challenges.

Justin J. Boutilier is the Charles Ringrose assistant professor in industrial and systems engineering at the University

of Wisconsin–Madison. His research focuses on combining optimization and machine learning to improve the quality, access, and delivery of healthcare in a variety of settings. He is particularly interested in global health projects involving emergency response or digital health technologies.

Auyon Siddiq is an assistant professor of decisions, operations, and technology management at the University of California, Los Angeles, Anderson School of Management. His research interests are in optimization, machine learning, and game theory, with applications in healthcare, urban mobility, and online labor platforms.